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DETERMINATION OF THE STABILITY AND CONTROL CHARACTERISTICS OF AIRPLANES FROM TESTS OF POWERED MODELS

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DETERMINATION OF THE STABILITY AND CONTROL CHARACTERISTICS OF AIRPLANES FROM TESTS OF POWERED MODELS

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SUMMARY

A technique of testing wind-tunnel powered models has been developed as a result of experience gained in the investigation of the static longitudinal- and lateral-stability and control characteristics of several powered models in the NACA 7- by 10-foot wind tunnel. As an important part of this technique, a minimum program of the tests considered necessary to specify satisfactorily the static stability and control characteristics for present-day airplanes has been tentatively established.

A discussion of the conditions to be investigated, methods of presenting and interpreting the data, and a suggested operating technique are given. Typical test data, illustrating some of the effects of power on the characteristics of a model of a low-wing single-engine airplane, are also presented.

INTRODUCTION

The National Advisory Committee for Aeronautics has undertaken an extensive investigation to determine the effects of propeller operation on the longitudinal- and lateral-stability and control characteristics of modern airplanes. The possible adverse effect of propeller operation on stability and control characteristics has long been appreciated, but only recently has there been an increase in the power output of the engine-propeller unit to a point where the effects of propeller operation have become definitely serious.

The marked effects of propeller operation on the aerodynamic characteristics of a model of a typical single-engine, low-wing, pursuit-type airplane (fig. 1) are illustrated by figures 2 to 5. The decrease in static longitudinal stability and the change in longitudinal trim resulting from propeller operation are shown in figure 2 and the increase in the control effectiveness caused by the slipstream is illustrated in figure 3. The decrease in the effective dihedral caused by power is illustrated in figure 4 and the effects of power on trim and weathercock stability are shown in figure 5.

Methods for computing the effects of power on the static longitudinal stability are given in references 1 and 2 but, as the authors themselves point out, the procedure is difficult and uncertain at best. The method of calculation of power-on lateral-stability characteristics is even more vague. The simplest solution to the problem is to run power-on model tests, especially since the agreement obtained between powered-model tests and flight tests indicates that this method is quite accurate (fig. 6).

Methods of analyzing power-on wind-tunnel data for dynamic flight conditions have been discussed in reference 3. This discussion indicated that the data obtained from powered-model tests will not only give an excellent indication of the probable static-stability characteristics of the airplane but also will permit a more accurate analysis for dynamic flight conditions. There are many important factors, however, that may adversely affect the flying qualities of an airplane, especially one with free controls, but that cannot be determined from wind-tunnel tests and must therefore be ignored in this discussion of aerodynamic qualities. These factors include the excessive control friction present in many airplanes, the lag of servo-control systems, the weight moments of the control surfaces, and the elastic constants of the control system.

Because power-on tests are generally more expensive, require an additional tunnel operator, and usually require more time to run than ordinary tests, the development of a simple operating procedure is important. Furthermore, the number of tests made should be the minimum number necessary to determine whether the stability and control characteristics of the airplane will be satisfactory.

A discussion of the conditions to be investigated and a tentative minimum test program are presented in part I of this report. A suggested operating procedure is presented in part II. In part III are given the results of some tests of a typical powered model as well as a discussion of the effects of power on stability.

I. CONDITIONS TO BE INVESTIGATED AND TESTS NECESSARY

POWER CONDITIONS

General Conditions

A prerequisite for the development of a satisfactory operating technique for powered-model tests is the selection of the airplane power conditions that should be simulated. Inasmuch as the adverse effects of power on the characteristics of the airplane result from the propeller slipstream and the direct propeller forces, reproduction of the power conditions for which the slipstream velocities and propeller forces are greatest will be desirable. As the airplane often operates without power, that is, with the propeller windmilling, and may have unsatisfactory characteristics in this condition, the windmilling state must also be investigated. The propeller-removed condition is never encountered in flight, but data for this condition are always desirable for purposes of comparison.

Longitudinal Characteristics

The airplane in normal flight may operate over its speed range with any one of several power conditions, including level-flight power, constant angle-of-climb power, constant power, and idling engines. Wind-tunnel data may be obtained either by simulating the appropriate power condition on the model throughout its angle-of-attack range or by repeating the angle-of-attack tests at several values of constant thrust coefficient and then cross-plotting to the desired thrust coefficient (power condition) at each lift coefficient. Although this constant thrust method of test procedure is very simple, the number of tests necessary and the labor involved in cross-plotting the results makes it undesirable.

Of the several airplane power conditions previously mentioned, the constant power condition is most generally satisfactory for routine investigations. It represents a very frequent condition in flight, is quite readily reproduced in the wind tunnel, and requires no estimation of the aerodynamic characteristics of the airplane such as is required for the reproduction of level-flight power. Furthermore, it may be made to represent the most severe conditions that are to be encountered, because with constant full-rated power the maximum possible thrust coefficients at any lift coefficient are obtained. The static stability measured in the tunnel with constant power operation will correspond closely to the stability encountered in flight, because the normal method of determining the stability of an airplane is to measure its ability to return to an original steady-state condition after being displaced slightly from that condition. Throughout this cycle from steady state to steady state, the throttle is left fixed, a condition corresponding approximately to that of constant power output. The condition of constant power output applies throughout the flight range, regardless of the amount of power; thus, if the power used is greater than the power necessary to maintain level flight at the given lift coefficient, the airplane climbs; if less, the airplane dives. In any case, however, an equilibrium, or steady-state condition for which the stability may be determined, if altitude changes are neglected, is soon reached.

The slope of the curve of pitching moment against lift obtained by constant power operation is a measure of the static longitudinal stability of the airplane operating under similar conditions. It has been shown that this slope is approximately proportional to the dynamic-stability constant E of classic stability theory. This result might have been expected since the dynamic-stability constant E defines the long-period oscillations in which the various changes occur slowly enough for the engine-propeller unit to maintain a condition of constant power output. For short-period oscillations, however, which occur so fast that the engine-propeller-unit characteristics do not have time to change and are therefore more nearly at constant thrust conditions than at constant power conditions, the representation may not be valid. As will be pointed out later by proper cross-plotting, the constant-thrust longitudinal-stability curves may be determined from the wind-tunnel data obtained for constant power conditions.

As the net effect of propeller operation is usually adverse for conventional tractor airplanes and as the flying qualities of the airplane are usually most affected when maximum power is applied, it is considered desirable to determine the stability and control characteristics at the flight condition of full-rated (or take-off) power as the most severe case to be encountered. The axial slip-stream velocity corresponding to a given power condition is largest when the air density is greatest; thus the maximum adverse power effects will usually be encountered with full-rated power at sea-level altitude, where the air is most dense.

The stability characteristics of the airplane should also be checked at one or more intermediate power conditions, because there are possible arrangements of airplanes for which the net effects of power are stabilizing. For example, the longitudinal stability is increased by power if the thrust axis is far enough above the center of gravity. Thus, the partial-power condition may be the critical condition.

Partial-power tests are also necessary in order to obtain the longitudinal-stability characteristics at various values of constant thrust coefficient by proper cross-plotting. The stability characteristics for constant thrust conditions determine the power-on stability derivatives and must therefore be used in computing the motions of the airplane.

As was shown in figure 2, the windmilling or idling propeller has a rather powerful destabilizing influence. Inasmuch as the propeller is frequently idled during the operation of the airplanes, it is necessary to investigate the stability characteristics for this condition of propeller operation. In the case of idling propeller, the air stream forces the propeller to rotate against the engine friction forces. Thus, the mechanical condition of the engine, the flight speed, and the setting of the propeller-speed mechanism determine the amount of negative thrust developed by the propeller. Tests indicate, however, that the amount of negative thrust is not very critical for the usual flight conditions. For tests of models of dive bombers with braking propellers, the problem may be more critical and some attempt to simulate the exact airplane engine-propeller characteristics for these conditions should probably be made.

Lateral Characteristics

The lateral-stability and control characteristics of the airplane are markedly influenced by the axial slipstream velocity and the slipstream rotation. The power conditions for which these factors are large should therefore be investigated. It should be noted that, because the lateral characteristics are investigated at a constant angle of attack, the tests will actually be made at a constant thrust coefficient. The value of the thrust coefficient, however, is determined by the power conditions to be simulated. The rotational velocities are more important in the lateral-stability investigation than in the longitudinal-stability investigations. For this reason the rotational velocities should be reproduced (see part II) rather accurately. If it is impossible to reproduce them with any one blade angle, it will be necessary to repeat some of the tests with a range of blade angles and extrapolate the results to the torque coefficient of the airplane for the desired condition.

Some of the lateral characteristics, such as rudder effectiveness and weathercock stability, are usually improved by power. Thus, these factors may be satisfactory for power-on flight but undesirably small for gliding. The condition of windmilling propellers should therefore be investigated.

FLIGHT CONDITIONS

General Conditions

The basic conditions of flight are the take-off, the climbing, the gliding, the landing, and the stalled or spinning conditions. In general, each of these flight conditions must be investigated with the various representative power conditions that may be encountered for the particular flight condition. Thus, full-rated power should be used for take-off, climbing, landing, and stalled flight; about half-rated power should be used for the climbing and landing conditions; and windmilling propellers should be used for gliding, landing, and stalled states. The climbing- and gliding-flight conditions should be investigated over the complete lift-coefficient range of the airplane, from the minimum lift coefficient (dive) to the maximum lift coefficient. Negative lift coefficients (inverted flight) should also be investigated for highly maneuverable airplanes. The take-off and the landing condition need be investigated only over the moderate- and the high-lift range.

The position of the wing flap, of the landing gear, of the cowl flap, etc. on the model should correspond to that on the airplane at the flight condition to be investigated. If the airplane is designed to take off with flaps undeflected, however, some of the tests for the climbing condition may be used as approximations to the take-off condition since the power condition is nearly the same and the positions of the cowl flap and the landing gear are usually not of too great importance in stability investigations. Similarly, if the airplane is to take off with flaps fully deflected, some of the landing-condition tests with full power may be used to give an indication of the take-off characteristics.

The longitudinal- and lateral-stability, the control, and the trim characteristics should be investigated for each of the combinations of attitude and power unless, for some special reason, it is known that the model under test will be satisfactory for a particular condition. Such is often the case when, for instance, only minor modifications have been made on an existing design that has already been proved satisfactory. It will then be necessary to test the model for only the few characteristics that may have been altered by the modifications. Even in an investigation of a completely new design, lack of time and money makes it practically impossible to test the model for all flight conditions. It is thus necessary to make some attempt to determine the probable critical flight conditions and to restrict the investigation to those conditions.

Any attempt to specify the probably critical conditions that may be encountered in flight must be based on past experience and is thereby limited to conventional types of airplane. Although many of these critical conditions are not actually dangerous, they definitely affect the flying qualities of the airplane adversely.

Longitudinal Characteristics

Probable critical flight conditions.- The elevator movement required to trim the airplane over the complete speed range is considered an excellent measure of static stability by pilots and flight-test engineers. (See reference 4.) This elevator movement is very small for most modern high-power airplanes in the cruising or climbing condition. Excessive control manipulation is consequently required in gusty air. Furthermore, the stick position will give little indication of the flight attitude and the airplane may be inadvertently stalled. The small elevator movement is usually most marked for flight conditions in which large amounts of power are used throughout the speed range.

The stick-force characteristics are no better criterion of the flight speed than is the stick position and, in addition, the stick-force characteristics may be masked by excessive friction. These forces also depend critically upon the trim-tab setting. The low longitudinal stability usually makes the trim tab appear too sensitive and, inasmuch as the variation of elevator-control force with lift coefficient is determined by the trim-tab setting, it is necessary to determine the effectiveness of the trim tabs. The control forces may be critical for almost any flight condition.

The change in trim caused by the application of power may be critical, especially if the power must be applied so rapidly that the elevator cannot be deflected in time to maintain trim conditions. Such a situation may arise if the trim tabs cannot be adjusted rapidly enough to keep the stick forces reasonably low. Some of the flight conditions under which sudden changes in the applied power would be encountered are as follows: during the landing approach when for some reason the airplane cannot land and take-off power must be applied rapidly; during the take-off where the engine fails, at least temporarily; in climbing flight when the engine fails; and in gliding or cruising flight of a military airplane, which must suddenly escape the enemy by applying full power. As the greatest trim changes due to power are usually found for the flap-deflected condition, the application of take-off power to the airplane in the landing condition is perhaps the most critical of these possible conditions.

Some other flight conditions, in which the characteristics of the airplane may be unsatisfactory or even critical, may be mentioned as follows: In landing, the elevator may not be powerful enough to hold the airplane in the attitude for maximum lift because of the effect of the ground on the stability (reference 5). In accelerated maneuvers, the required elevator deflections may be unobtainable because the stick forces exceed the pilot's strength (reference 3). In a stall or spin, the elevator effectiveness may be inadequate or the stick forces too high for recovery. In any flight attitude with free controls, the stability will depend upon the trim-tab setting and may be undesirably low.

Necessary tests.- In many cases, fortunately, the same series of tests may be used to estimate the characteristics of the airplane for several of the probable critical conditions already described as well as to determine certain model characteristics that must be used to correct the tunnel data to flight conditions. The operating procedure will be described in part II. The lift, the drag, the pitching moment, the power parameters - thrust coefficient, torque coefficient, advance-diameter ratio, efficiency, and blade angle - and the elevator hinge moments are measured at various angles of attack from almost zero lift to the stall for several elevator and stabilizer settings for the various model and power conditions to be investigated. A few elevator tests should be run with the model simulating the climbing and the gliding conditions at angles of attack above the stall to determine the elevator and stability characteristics in a stall or a spin, and some elevator tests should be run at negative lift coefficients to determine the characteristics for conditions simulating inverted flight for highly maneuverable airplanes. The effect of the trim tab upon the stick-force characteristics for some of the conditions must also be checked. Elevator-free tests need not be run, because the hinge moments are measured in the elevator tests and, by proper cross-plotting, the elevator-free characteristics may be determined. If it is impossible to measure the hinge moments, however, elevator-free tests should be made. The effect of trim-tab setting upon the elevator-free characteristics should be checked.

Tail-removed tests should be made to facilitate analysis of the data, although such tests are not absolutely necessary. These tail-removed tests are highly important if the original tail surfaces are unsatisfactory and must be redesigned. Air-flow surveys at the tail region are also very desirable.

The purpose of the stabilizer tests is twofold: first, to determine the stabilizer setting required to trim the airplane in the cruising attitude, and second, to determine the stabilizer effectiveness $\partial C_m/\partial i_t$ for the various power and model conditions, where C_m is pitching-moment coefficient and i_t is stabilizer angle. (All symbols used hereafter in the text are completely defined in the appendix.) The stabilizer-effectiveness data are used to correct the measured wind-tunnel pitching-moment data for the effects of the jet boundary as well as to give a measure of the air-flow velocity at the tail surfaces (amount of slipstream passing over the tail, etc.). Tests with two different stabilizer settings are required for each model and power condition to be investigated. The stabilizer settings should bracket the conditions of trim within the flight range and should be at least 3° apart to maintain a reasonable degree of accuracy.

The elevator tests are made with the stabilizer set as it will be on the airplane, probably to trim at the cruising attitude. About three or four elevator settings are usually necessary for each model and power condition to be tested. The elevator settings are so chosen as to trim the model over the complete lift range. These elevator tests may be used to estimate the probable characteristics of the airplane at the various critical conditions. The elevator movement required to trim the airplane over the complete speed range, the elevator stick-force characteristics, the changes in pitching-moment and stick-force trim conditions due to power, the effect of changing the center-of-gravity location, the effectiveness of the elevator in producing accelerated maneuvers, and the elevator effectiveness and stick forces in a stall or spin may all be determined from these tests.

The tests to determine the elevator effectiveness for landing should be made in the presence of a ground board. (See reference 5 for a description of such tests.) If, however, it is impossible to make ground-board tests, the additional effects due to ground may be estimated from theoretical considerations.

Tests to determine the optimum mode of propeller rotation for multiengine airplanes should be made if the mode is not determined by other considerations.

<u>Presentation and analysis of data</u>.- When the airplane is in equilibrium flight, that is, in a steady-state condition, it is always trimmed ($C_m = 0$). The model need not necessarily be trimmed when tested, but to analyze the test

data correctly, it is necessary to determine the static-stability characteristics for trim conditions, since the static stability does depend upon the initial tail load (elevator setting) for power-on tests in which constant power operation is used. The usual measure of static longitudinal stability is the slope of the pitching-moment curve dC_m/dC_L. The slope of the pitching-moment curve dC_m/dC_L must therefore be determined at $C_m = 0$ for each elevator setting tested and then plotted as a function of the trim lift coefficient. Another measure of static longitudinal stability is, simply, the elevator angle required to trim the airplane over the lift range. The two measures of static stability are closely related. For qualitative work the elevator movement required to trim the airplane over the complete speed range is not only a good measure of stability but also allows direct comparison with flight because it is readily determined in flight tests.

The stick-free stability characteristics should be determined for trimmed conditions (trim by means of tabs) also. The plot of elevator angle for trim as a function of lift coefficient such as is used to define the stick-fixed characteristics will not define the stick-free characteristics, however, because the curves would be the same (stick free or stick fixed) for any given model or power condition. The actual slopes of the pitching-moment curves at $C_m = 0$ (for the trim-tab setting for $C_{h_e} = 0$) must be used for the analysis. For purposes of comparison it will be advantageous to have the slopes dC_m/dC_L for the stick-fixed condition also. Thus it will usually be simpler to analyze the data for static stability and for trim if it is summarized by plotting elevator angle required to trim against lift coefficient for each model and power condition tested and for each center-of-gravity location to be used and also by plotting the trimmed slopes dC_m/dC_L as functions of lift coefficient for the stick-free and the stick-fixed conditions.

If it is desired to calculate either the motions of the airplane or its short-period dynamic-stability characteristics, it will be necessary to cross-plot the constant-power pitching-moment curves to obtain constant-thrust pitching-moment curves. The slope of the constant-thrust curves is $\partial C_m/\partial\alpha$ (the change in pitching moment due only to a change in angle of attack), and the slope of the constant-power curves is $dC_m/d\alpha$ (the complete change in pitching moment due to a change in both angle of attack and forward velocity). The elevator effectiveness $\partial C_m/\partial \delta_e$ must also be determined as a function of lift coefficient for the dynamic-stability calculations.

The methods of analyzing wind-tunnel data for dynamic flight conditions given in reference 3 may be used to compute the ability of the elevators to perform accelerated maneuvers and to determine whether the stick forces in accelerated maneuvers will become excessive.

The hinge-moment data must be examined rather critically in order to determine whether the stick forces will ever become excessive for any trim-tab setting likely to be used. The measured hinge-moment characteristics must be converted to stick force so that they will be in exactly the units, pounds, that the pilot will have to exert. The trim-tab data are quite important because the variation of elevator stick force with lift coefficient depends critically upon the trim-tab setting. The trim-tab data are also important in computing the stick-free stability characteristics.

If tail-removed tests are made, the increment of pitching moment due to the tail and thus the tail load may be calculated. A knowledge of the contribution of the tail to the pitching moments of the complete airplane is necessary, provided that the stability or the control characteristics are unsatisfactory and a new tail is to be designed. Also, if surveys are made of the air flow at the tail, redesigning the tail surfaces will be greatly facilitated.

Lateral Characteristics

Probable critical flight conditions.- Large changes in longitudinal trim are associated with sideslip under power for most single-engine and for many multiengine airplanes. The trim changes occurring at moderate angles of sideslip are often so large that the elevator power available is not adequate to maintain even moderate angle of sideslip without having the airplane dive or stall out of the sideslip.

The problem of trimming the airplane in roll and in yaw with large amounts of power or with unsymmetrical power in multiengine airplanes is always difficult and often critical. Thus, either because the controls lack sufficient power or because the control forces are too high to permit large deflections, it may not be possible to hold the airplane at zero yaw when operating with unsymmetrical power. Single-engine airplanes are also likely to experience trouble in this respect because of slipstream rotation. In some cases, full rudder is required to hold the airplane at zero yaw with flaps down and full power. Trim changes in roll caused by motor torque have also been found objectionable on several airplanes. All these trim changes are most marked in those flight conditions in which the speed is low and the power applied is large.

Inasmuch as power usually increases the value of $\partial C_n/\partial\psi$ (either rudder fixed or free) at small angles of yaw, the flight condition at which the directional stability is most likely to be unsatisfactory is the landing condition when the propeller is windmilling. At large angles of yaw with the rudder fixed or free, the directional characteristics are probably the least satisfactory under the high-thrust condition.

The slope of the rolling-moment curve $\partial C_l/\partial\psi$ is a measure of the effective dihedral, a value of about 0.0002 being equivalent to 1° of dihedral. (See reference 6.) The influence of power on the dihedral is quite marked. For one single-engine model tested in the 7- by 10-foot tunnel the effective dihedral was reduced 10° by about 70-percent rated power applied in the landing condition. Multiengine models usually do not lose as much dihedral effect when power is applied as single-engine models. The loss in effective dihedral caused by power is usually greatest for conditions of slow-flight speed with flaps deflected and with high power.

The stability and trim characteristics are affected by the direction of rotation of the propellers of multiengine airplanes. It is thus important to determine the mode of rotation giving the most desirable characteristics. Since longitudinal stability characteristics are also affected, a compromise may be necessary.

An airplane, to be satisfactory under all conditions, should possess not only static stability but dynamic stability. Dynamic stability requires that the weathercock stability and the effective dihedral lie within certain limits. These limits depend not only on the various aerodynamic characteristics of the airplane but also upon the radii of gyration, the mass density of the airplane, and the control-surface characteristics for control-free flight. Desirable limits of the static-stability criterions for a particular airplane may be estimated by use of references 7, 8, and 9. Inasmuch as the static-stability characteristics vary through the flight range, it will be necessary to determine whether these characteristics lie within the required limits for each condition of flight.

Necessary tests.- It would, of course, be desirable to make lateral-stability (yaw) tests simulating each of the basic flight conditions at all lift coefficients. As the number of tests is prohibitive, however, only a few basic conditions at representative lift coefficients are chosen for tests. For most routine investigations these conditions are the high-speed attitude with full power, a climbing attitude (moderate lift coefficient with flaps neutral or partially deflected) with full power, and the landing attitude (2° below the power-off stall with flaps full down) with windmilling propellers and with full power. Partial-power and power-off tests should be included, if possible, to show the effect of power.

Each basic condition should be investigated throughout the yaw range from 0° to $\pm 50^{\circ}$, the usual six components, the power parameters, and the rudder hinge moments for several rudder and one or two elevator settings being determined. Care must be maintained to select the values of rudder deflection to be investigated in such a way that will trim the model over the complete yaw range, including both positive and negative angles. As the elevator effectiveness for power-on tests varies with angle of yaw, elevator tests should be made in yaw to determine whether the elevators are powerful enough to hold a given angle of sideslip. Aileron tests are usually made for the high-speed and the landing conditions and may be made with practically any power condition convenient. The measurements necessary for the aileron tests are the usual six components and the aileron hinge moments.

These tests constitute the minimum number of tests necessary to estimate the lateral-stability and control characteristics of the airplane. If the characteristics prove unsatisfactory or if a more detailed study of the characteristics of the airplane is desired, additional tests must be made. The recommended additional tests are the tail-removed tests, power-on and power-off, and surveys of the air flow (dynamic pressure and direction) at the tail. These tests greatly simplify the problem of redesigning the tail surfaces, if redesigning is necessary.

Presentation and analysis of data. - The lateral-stability data obtained from the model tests should be analyzed for steady-state trimmed-flight conditions. It is difficult to obtain data for the model trimmed with respect to all three axes: pitch, roll, and yaw. There are two practical methods of obtaining data for trimmed conditions.

One method is to transfer the data from the usual wind-tunnel balance axes (the wind axes) to some other system of axes such that the deflection of any one of the three controls will affect only the moments about the axis that control is normally designed to affect and will not appreciably affect the moments about either of the other two axes. For example, in order to determine the effective dihedral $(\partial C_l/\partial \psi)$ it is necessary to have the model trimmed in pitch and in yaw; otherwise, components of pitching moment and of yawing moment will be present in the rolling moment. If, however, the data are transferred to a system of body axes such that the X axis lies in the plane of symmetry, no component of pitching moment about the Y axis due to elevator deflection can affect the rolling moment about the X axis. If the X axis not only lies in the plane of symmetry but also passes through the center of pressure of the vertical tail surface, no component of yawing moment about the Z axis due to rudder deflection can affect the rolling moment about the X axis.

After the transfer has been made, the slopes $\partial C_n/\partial \psi$ and $\partial C_l/\partial \psi$ may be easily determined for trim conditions, because the other moments have no effect about these axes. For most airplane models the components of rolling moment due to rudder deflection are rather small, because the center of pressure of the tail is usually fairly near the relative wind vector through the center of gravity, at least for the critical case of minimum speed (with high thrust coefficients). Thus, the component of rolling moment due to rudder deflection may generally be neglected and it will be necessary only to transfer the data to the so-called stability axes instead of to the body axes. Transferring the data to the stability axes is simpler than transferring them to the body axes. The stability axes are a system of axes in which the X axis is the intersection of the plane of symmetry of the airplane with a plane perpendicular to the plane of symmetry and parallel with the relative wind direction, the Y axis is perpendicular to the plane of symmetry, and the Z axis is in the plane of symmetry and perpendicular to the X axis. It must be emphasized that the use of this system of axes corrects the data for untrimmed pitching moments only. Another advantage of the use of the stability axes is that this system of axes is most easily used for dynamic-stability calculations. For the convenience of the tunnel operator, the basic transfer equations from the wind to the stability axes along with some approximate slope equations that apply at angles of aw near zero only are herewith presented:

$$C_L = C_L' \tag{1}$$

$$C_D = C_D' \cos\psi - C_Y' \sin\psi \tag{2}$$

$$C_Y = C_Y' \cos\psi + C_D' \sin\psi \tag{3}$$

$$C_m = C_m' \cos\psi - b/c\ C_l' \sin\psi \tag{4}$$

$$C_l = C_l' \cos\psi + c/b\ C_m' \sin\psi \tag{5}$$

$$C_n = C_n' \tag{6}$$

Approximate slope equations at small angles of yaw are

$$\frac{\partial C_Y}{\partial\psi} = \frac{\partial C_Y'}{\partial\psi} + \frac{C_D'}{57.3} \tag{7}$$

$$\frac{\partial C}{\partial\psi} = \frac{\partial C_l'}{\partial\psi} + \frac{c}{b}\,\frac{C_m'}{57.3} \tag{8}$$

$$\frac{\partial C_n}{\partial\psi} = \frac{\partial C_n'}{\partial\psi} \qquad \text{(For any angle of yaw)} \tag{9}$$

where a single prime indicates wind axes and no prime indicates stability axes.

The second method of obtaining data for the model in trimmed flight is to cross-plot directly the wind-axes data (tunnel data transferred only to the center of gravity of the model) in order to determine the control deflections necessary to trim the model about all three axes. This method assumes no interaction or interference between the controls and the cross plots have to be made in the style of successive approximations. The labor involved, however, will usually be less than the labor involved in the transfer to the stability axes before the cross plots are made. (The cross plots must be made to analyze the data properly.)

The plots of the control-surface deflection necessary to trim the model at each angle of steady sideslip are not only convenient summary plots because they give a direct measure of the stability, control, and trim characteristics but also may be directly compared with results of flight tests. The angle of bank necessary to counteract the lateral force may also be computed for comparison with the angle of bank measured during flight tests, if desired. Part of the measured lateral force is due to the rudder setting, and the value of the lateral force used consequently depends upon the control deflections required for trim.

In order to calculate the motions of the airplane and the dynamic-stability characteristics, it is necessary to have the trim slopes of the rolling-moment, yawing-moment, and lateral-force curves near zero yaw. These slopes are to be obtained with respect to the stability axes but may be obtained from the original wind-axes data and corrected to the stability axes by use of the approximate slope formulas previously given.

The direct effect of the controls ($\partial C_n/\partial \delta_r$ and $\partial C_l/\partial \delta_a$) and the secondary effects ($\partial C_n/\partial \delta_a$ and $\partial C_l/\partial \delta_r$) should be determined about the stability axes. For practical purposes wind-axes data may be used provided that the rolling effectiveness of the lateral controls is determined at zero yaw where the wind and stability axes are the same, since the yawing moment is always the same about either the wind or the stability axes. These data are of value both for comparison of static data and for dynamic-stability and resulting-motion calculations. These calculations must be made if it is desired to estimate the effectiveness of the control surface in producing the desired motions of an airplane because the coupling of the yawing and rolling motions resulting from small control deflections may generate motions opposite to those that the control deflections were designed to produce. The period and damping of any oscillation should be estimated for the various flight conditions.

The control forces and effectiveness required for spin recoveries must also be checked, insofar as possible, with the static data available from the tests made.

Summary of Tests Required

A summary of the tests required for a routine investigation of the static-stability and control characteristics of a model is presented in tables I and II. The number of tests indicated is believed to be the smallest number consistent with a satisfactory determination of the static-stability characteristics. As pointed out previously, for a more complete investigation it would be desirable to increase the number of power and model conditions, to add propeller-removed tests, ground-board tests, tail-removed tests, and dynamic-pressure and angle surveys at the tail. For multiengine models all tests should be repeated with various modes of propeller rotation and with asymmetrical power. If the airplane propeller characteristics cannot be closely reproduced by one model blade angle, blade-angle tests should be made.

II. SUGGESTED WIND-TUNNEL OPERATING TECHNIQUE

DISCUSSION OF THE CRITERIONS OF SIMILITUDE

The tests to be run and the airplane power conditions to be used for those tests have now been selected. There remains the problem of determining a simple, rapid wind-tunnel operating procedure that will properly simulate the power conditions selected. The criterions of similitude will be established, and the general methods used to estimate the numerical values of the airplane criterions and the methods necessary to reproduce those criterions for the model tests will be given in the following sections.

Tests of models can never be expected to exactly reproduce full-scale conditions unless the model is the airplane and the air stream has free-air characteristics, that is, flight tests. This statement is fundamentally true for any type of test, power-off or power-on, because there are always some conditions of similitude that cannot be met or that even conflict with other conditions. Fortunately, however, all the conditions are not of equal importance and, if the principal effects of the various factors are reproduced, results that are correct for all practical purposes may be obtained.

In practically all power-off wind-tunnel stability investigation the effects of Reynolds number, turbulence, surface roughness, interference of omitted parts, Mach number, etc. are ignored. The only criterion of similitude that is usually met is that the model be built to scale with only a few omitted parts. In making power-on tests the only important additional criterion of similitude is that the relative slipstream velocities be the same on the model as on the full-scale airplane. If the slipstream is reproduced, the propeller forces will automatically be reproduced because the propeller forces are equal to the increase in momentum of the air in the slipstream. It would require a detailed air-flow survey of the region in and near the slipstream of both the model and the airplane to determine properly whether the slipstream has been reproduced. Such surveys are impractical and it becomes necessary to determine some simple criterions for reproducing the slipstream.

The important airplane slipstream characteristics may be considered reproduced on the model when the thrust coefficient, the torque coefficient, and the normal-force coefficient of the model are the same as those of the airplane. These criterions of similitude are based upon elementary momentum theory, which indicates that the axial slipstream velocity ratio is a function of the thrust coefficient, the ratio of the tangential to the axial velocity (helix angle) is proportional to the ratio of the torque coefficient to the thrust coefficient, and the angular direction of the slipstream is a function of the normal-force coefficient and the thrust coefficient. The efficiency may be considered a criterion of the energy lost in the slipstream due to eddies, temperature rise, and altered velocity distribution.

Fortunately, experience has shown that it is usually not necessary to exactly reproduce the slipstream in order to secure satisfactory results in most power-on stability investigations. The effects of each of the variables should be kept in mind, because experience has indicated that some of the factors affecting these variables are relatively unimportant for some types of test on some airplanes. The same factors are of utmost importance for other types of test or for other airplane types.

DETERMINATION OF FULL-SCALE PROPELLER CHARACTERISTICS

Positive Thrust Condition

Before it is possible to reproduce the airplane slipstream conditions, it will be necessary first to calculate the full-scale propeller characteristics expressed in coefficient form. The methods used to calculate the propeller characteristics are simple and straightforward. The thrust coefficient, the torque coefficient, and the normal-force coefficient of the airplane propeller must be determined as functions of the airplane lift coefficient for the various power conditions to be investigated. A knowledge of the advance-diameter ratio, the efficiency, and the blade angles of the propeller is also highly desirable.

Only the calculations necessary to determine the characteristics of a constant-speed propeller delivering constant power will be outlined here. The same basic ideas are used, however, to calculate the characteristics of fixed-pitch propellers or propeller-engine combinations operating under other power conditions.

The brake horsepower and the propeller speed and diameter are known. The procedure for the calculations is as follows (the symbols used are standard NACA symbols and are defined in the appendix):

1. For several values of lift coefficient, compute the airplane velocity V (ft/sec) from the formula

$$V = \sqrt{\frac{2W}{\rho S}} \sqrt{\frac{\cos \theta}{C_L}}$$

As the angle θ has not yet been determined, it will be necessary to assume a value of $\cos \theta = 1$; that is, level flight must be assumed. No appreciable error is introduced by this procedure, for the thrust coefficients calculated for use of level-flight conditions are only about 3 to 5 percent low even in the high-lift range, and this small error will later be corrected.

That is, level flight velocity

$$V_{L.F.} = \sqrt{\frac{2W}{\rho S}} \sqrt{\frac{1}{C_L}}$$

2. Compute $V_{L.F.}/nD$ for each value of lift coefficient

3. Calculate the power coefficient C_P by the following formula

$$C_{P_{(actual)}} = \frac{\text{engine power}}{\rho n^3 D^5}$$

4. From a propeller-characteristics report (for example, reference 10) giving the characteristics of a propeller and nacelle combination similar to that of the airplane, determine the C_T, η, and β for the previously determined values of $V_{L.F.}/nD$ and C_P. If the full-scale propeller differs very much in plan form and thickness from the assumed propeller, it may be desirable to correct the power coefficient C_P for these differences. Hamilton Standard Propellers, Division of United Aircraft Corporation, has determined a correction for plan form called activity factor where

$$K_{A.F.} = \text{activity factor ratio} = \frac{C_{P_{(chart)}}}{C_{P_{(actual)}}}$$

and an approximate correction for blade thickness. In the absence of Hamilton Standard Propeller data, the activity factor may be computed by the formula

$$A.F. = \frac{100000}{53} \int_{0.2}^{1.0} \frac{c_p}{R} \left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)$$

for the assumed (chart) propeller and for the actual propeller. The thickness correction may usually be neglected.

5. Calculate the approximate thrust coefficient $T_{c}'_{L.F.}$ in terms of wing area and level-flight dynamic pressure from

$$T_c{}'_{L.F.} = \frac{T}{q_{L.F.} S} = \frac{C_T}{\left(\frac{V_{L.F.}}{nD}\right)^2} \left(\frac{2D^2}{S}\right)$$

6. If airplane drag for the propeller-removed condition is available, or may be estimated, make an estimate for the angle θ since

$$\theta = \tan^{-1}\left(\frac{T_c{}' - C_{D_{power-off}}}{C_L}\right)$$

or approximately

$$\theta = \tan^{-1}\left(\frac{T_c{}'_{L.F.} - C_{D_{power-off}}}{C_L}\right)$$

7. For a better approximation to the true V/nD, determine

$$\frac{V}{nD} = \frac{V_{L.F.}}{nD} \sqrt{\cos \theta}$$

8. For the more exact thrust coefficient, determine

$$T_c{}' = \frac{C_T}{\left(\frac{V}{nD}\right)^2} \frac{2D^2}{S}$$

where the value of C_T for $(V/nD)_{L.F.}$ may be used

$$V = V_{L.F.} \sqrt{\cos \theta}$$

$$T_c{}' = \frac{C_T}{\left(\frac{V_{L.F.} \sqrt{\cos \theta}}{nD}\right)^2} \frac{2D^2}{S} = \frac{T_c{}'_{L.F.}}{\cos \theta}$$

9. Compute the propeller thrust coefficient in terms of the propeller dimensions, if desired

$$T_c = T_c{}' \left(\frac{S}{2D^2}\right) \quad \text{or} \quad T_c = \frac{C_T}{(V/nD)^2}$$

10. Compute the torque coefficient Q_c as follows:

$$Q_c = \frac{T_c}{\eta}\left(\frac{V}{nD}\right)\frac{1}{2\pi}$$

11. Calculate the propeller normal-force coefficient N_c from Glauert's equations by use of experimentally determined average propeller curves (see reference 1) of K:

$$N_c = \frac{K \sin \alpha}{\left(\frac{V}{nD}\right)^2} \qquad \frac{N}{3} = \frac{\text{normal force}}{\rho V^2 D^2}$$

The full-scale propeller-thrust coefficient, the normal-force coefficient, the torque coefficient, the efficiency, the blade-angle variation, and the advance-diameter ratio have now been determined. Typical calculated characteristics are illustrated in figure 7.

It should be noted here that the airplane propeller characteristics just computed are the estimated propulsive characteristics, not the actual forces or moments that really determine the slipstream motion.

Methods for determining the amount of air flow through the cowling have not been given, but the air flow should be determined and reproduced on the model, if feasible, because the air flow will affect the distribution of slipstream velocities and may even be critical for some airplanes.

Negative Thrust Conditions

The negative thrust characteristics of airplanes are difficult to estimate. In reference 11 is given a summary of the data available on negative thrust characteristics along with a small amount of engine-friction data.

The destabilizing effects of model propellers operating at negative thrust do not seem to be very critically dependent upon the blade angle used. For this reason no attempt will be made to repeat here the information given in reference 11. Some special flight conditions, however, such as the use of the propeller for a dive brake, may require an accurate reproduction of negative thrust.

MODEL PROPELLER CHARACTERISTICS

Propellers for the usual moderate-sized wind-tunnel models are of fixed-pitch construction. Obviously, they cannot exactly reproduce the characteristics of a full-scale constant-speed propeller but, by the proper selection of the blade angle, the errors due to this factor may be made quite small. In figure 7 are shown not only the calculated characteristics of a full-scale constant-speed propeller but also the calculated characteristics of the propeller operated as a fixed-pitch propeller set at various blade angles but delivering the same thrust coefficients.

From these curves it may be seen that, if a blade angle of about 23° or 24° is used, the characteristics of the constant-speed propeller will be reproduced almost exactly by the fixed-pitch propeller. The calculated increment of pitching moment due to the propeller normal force and to the change in air-flow angle at the tail caused by the normal force is also included in figure 7. A constant blade angle of about 23° or 24° reproduces these pitching-moment increments just as well as it reproduces the propeller characteristics. These calculations for the constant-speed, the full-scale, and the fixed-pitch model propellers were all made from the same propeller data and are therefore for geometrically similar propellers. They do not include any Reynolds number effects, which may be quite large. Note that this value of blade angle (23°) applies only to this model. A similar value must be calculated for any other model or model conditions.

It is often necessary, or at least convenient, to use model propellers that are not geometrically similar to the full-scale propellers. The errors introduced by use of dissimilar propellers vary, of course, with the degree of dissimilarity. In general, though, the error is not much greater than the error caused by using a blade angle appreciably different from the optimum blade angle, provided that the propeller diameter used is correct. This error may be fairly large, however, as may be seen by comparing two widely different blade-angle curves of figure 7. Errors due to use of a propeller with the wrong diameter are a great deal more serious, because using the wrong diameter affects not only the rotational and normal velocities and their distribution but, more important, it alters the axial velocity, which is the most important effect to be reproduced. Every attempt should be made, then, to obtain the correct propeller diameter. <u>If the wrong diam-</u>

eter must be used, the thrust coefficient based upon wing area should be reproduced rather than the thrust coefficient based on disk area.

OPERATING CHART FOR THE WIND-TUNNEL OPERATOR

The most convenient method of determining the characteristics of the model propellers is to run propeller-calibration tests with the clean model mounted in the tunnel at about zero lift, that is, to measure the effective thrust coefficient, the torque coefficient, and the efficiency for various values of V/nD and blade angle. The effective thrust coefficient based on model wing area and on dynamic pressure is determined from the drag-scale readings taken with the propellers operating and with the propellers removed. Thus,

$$T_c' = C_{D_{\text{propellers removed}}} - C_{D_{\text{propellers operating}}}$$

The torque coefficients are determined either indirectly from calibrations of the model motors or directly from torque-meter readings. The efficiency may be calculated from the thrust, the torque, the motor speed, and the airspeed as measured. The propeller normal-force characteristics must be calculated, no simple method of measuring them being available.

A slight error in determining experimentally the propeller thrust may be caused by the fact that the effective thrust for a given actual thrust may be different on the airplane and on the model if the model cleanness or the air-stream turbulence is greatly different from that of the airplane. That is, the slipstream velocity is determined by the actual thrust force - not the effective thrust - and the actual slipstream values should be reproduced. If the transition is fixed at the same point on the model as on the airplane, this effect can be partly eliminated.

The blade angle for which the thrust, torque, normal-force, and efficiency characteristics most nearly represent the characteristics of the airplane constant-speed propeller may be determined by comparing plots of experimental model propeller data with calculated full-scale propeller data similar to figure 7. The effective thrust coefficient calibration for the selected blade angle is all that is required to determine the tunnel-operating conditions. In figure 8 is shown the evolution of a typical tunnel operating chart based on effective thrust coefficients alone for constant tunnel dynamic-pressure operation.

The computed airplane effective thrust coefficients for various lift coefficients and power conditions are shown in figure 8(a). A model propeller calibration is given in figure 8(b), and a composite of figures 8(a) and 8(b) is given in figure 8(c). The composite curve shows propeller speed in revolutions per minute plotted against lift coefficient for a given value of tunnel dynamic pressure.

Although the tunnel dynamic pressure is maintained constant for the propeller calibration and for all the tests, the actual tunnel velocity may vary somewhat because of changes in air density, which result in changes in the thrust delivered by the propellers. This error is usually small; in order to prevent its becoming large, the air density should be determined for each test and, if it varies markedly from the air density at the time that the propeller calibration was made, the operating charts should be corrected to the new density.

The first series of tests should be tare tests or stabilizer tests, as it is not important that the exact trimmed flight operating charts be used for these tests. The tares are fairly small quantities and the stabilizer tests are used only to determine the stabilizer effectiveness for the pitching-moment jet-boundary corrections and to determine the stabilizer angle for trim at cruising. If the first test is a stabilizer test, an operating chart similar to figure 8(c) is used. The second test, another stabilizer-angle test, is then made by operating the motors at the same speeds and at the same angles of attack as for the first test. From these two curves a power-on lift curve for trimmed flight conditions can be obtained. A curve of trimmed lift coefficient plotted against tunnel angle of attack is given in figure 8(d). For all succeeding tests made with this power condition, model condition, and blade angle, an operating curve of propeller speed as a function of tunnel angle of attack is used. This operating curve is obtained by combining figures 8(c) and 8(d) as shown in figure 8(e), the final operating chart.

The method of operating the propellers for yaw tests is quite simple. The model attitude is selected (high-speed attitude, climbing attitude, landing attitude, etc.) and the propeller speed corresponding to that attitude for zero angle of yaw is set and maintained throughout the yaw range tested. Although this operating procedure is the simplest possible, it reproduces the airplane-propeller conditions exactly for only small angles of yaw. At larger angles of yaw, the representation is not quite so accurate. The lift coefficient usually falls off at moderate and at high angles of yaw (in steady-state flight) and it would therefore be necessary either to change the flight attitude or to increase the airspeed in order to correct for this loss in lift coefficient at the initial angle of attack. The fact that either method of correcting for the loss in lift could be used by the pilot indicates the difficulties encountered in trying to represent exactly the flight conditions at high angles of yaw. <u>It is not usually considered worth while to use any more exact method of operating the model propellers for yaw test than to maintain constant propeller speed.</u>

III. TESTS OF A POWERED MODEL

MODEL AND APPARATUS

The model used was a 1/5-scale model of a low-wing, single-engine, pursuit-type airplane. It was made of mahogany with a hollow fuselage in which the motor and the hinge-moment balances were installed. A three-view drawing of the model is shown in figure 1.

TESTS

<u>Test conditions and procedure</u>.- The tests were made in the NACA 7- by 10-foot wind tunnel (references 12 and 13) at a dynamic pressure of 4.09 pounds per square foot, corresponding to a velocity of about 40 miles per hour at standard sea-level conditions. The test Reynolds number, based on this speed and a mean aerodynamic chord of 16.32 inches was about 500,000. The turbulence factor of the 7- by 10-foot tunnel is 1.6, so that the effective Reynolds number was about 800,000. The test procedure was similar to that indicated in part II.

Coefficients.- The results of the tests are given in the form of standard NACA coefficients of forces and moments based on model wing area, wing span, and mean aerodynamic chord. All moments are taken about a center of gravity located at 26.7 percent of the mean aerodynamic chord (fig. 1). The data are referred to the stability axes described in part I of the present report. The coefficients are defined in the appendix.

Corrections.- The lift, drag, and pitching-moment coefficients have been corrected for tares caused by the model support. These tares were obtained by preliminary tests with a dummy support for various model conditions. The effect of power upon the tares was estimated.

The angles of attack, the drag coefficient, and the pitching-moment coefficients have been corrected for the effects of the tunnel walls. The jet-boundary corrections applied were computed as follows:

Induced drag correction, $\Delta C_{D_i} = \delta \frac{S}{C} C_L^2$ (10)

Induced angle-of-attack correction,

$$\Delta \alpha_i = \delta \frac{S}{C} C_L \ (57.3) \tag{11}$$

Pitching-moment-coefficient correction,

$$\Delta C_m = \delta_a \frac{S}{C} \frac{dC_m}{di_t} C_L \ (57.3) \tag{12}$$

All corrections are added to tunnel data. In equations (10), (11), and (12)

δ jet-boundary correction factor (0.128)

δ_a additional jet-boundary correction factor (0.1)

C tunnel cross-sectional area (69.59 sq ft)

$\frac{dC_m}{di_t}$ change in pitching-moment coefficient per degree change in stabilizer setting as determined by tests

No jet-boundary corrections were applied to the yawing- and rolling-moment coefficients.

RESULTS

Characteristics in pitch.- The results of the pitch tests of the model with various power conditions are given in figures 9 to 12. Examination of these figures reveals the following facts:

1. The effect of propeller operation was destabilizing whether or not power was applied (figs. 9(a) and 9(b)). The windmilling propeller decreased the slope of the curve of pitching moment against lift about 25 percent below the propeller-removed value. Application of power decreased the slope of this curve still further, but the decrease was apparently not a direct function of the power applied.

2. The application of power increased the slope of the lift curve and the increase was approximately proportional to the amount of power (figs. 9(a) and 9(b)). The maximum lift coefficient also increased with power (fig. 9(a)).

3. An increase in propeller-blade angle slightly decreased the slope of the pitching-moment curve for the full-power condition (fig. 10(a)) but had no appreciable effect on the slope for the propeller windmilling condition (fig. 10(b)).

4. The stabilizer effectiveness was constant throughout the lift range for the propeller-windmilling condition, just as it usually is for the power-off condition. This effect is shown by the pitching-moment curves of figure 11(a), which are approximately linear and parallel. The stabilizer effectiveness increased with increasing thrust coefficient for power-on operation. This effect is shown by the diverging pitching-moment curves of figure 11(b) where the slope of the curves decreases with decreasing positive values of stabilizer angle. (The thrust coefficient increases with lift coefficient.)

5. The elevator effectiveness and the slope of the pitching-moment curves for the various deflections (fig. 12) and power conditions were affected in the same way that the stabilizer effectiveness and slope were affected.

Characteristics in yaw.- The results of the yaw tests of the model are presented in figures 13 to 17. The following points are worthy of note:

1. Power increased considerably the pitching moment due to yaw (figs. 13, 15, and 16).

2. The slope of the yawing-moment curve $\partial C_n/\partial\psi$ near zero yaw was increased by power (figs. 13, 14, 15, and 16).

3. The yawing moment at zero yaw was positive propeller-removed but became quite large negatively as power was applied (figs. 13, 15, and 16).

4. Power increased the slope of the lateral-force curve $\partial C_Y/\partial\psi$ (figs. 13, 14, 15, and 16).

5. Power decreased the slope of the rolling-moment curve $\partial C_l/\partial\psi$ (figs. 13 and 14).

6. In the high-speed attitude where the lift, the thrust, and the torque coefficients were low, changes in propeller-blade setting had no measurable effect on the aerodynamic characteristics (fig. 15(a). In the climb attitude where the lift, the thrust, and the torque coefficients were moderately large (fig. 15(b)) an increase in blade angle increased the negative yawing moment at zero yaw but did not change the slope of the yawing-moment curve near zero yaw appreciably, decreased the slope of the rolling-moment curve, and decreased the positive rudder-hinge-moment coefficient near zero yaw.

7. The rudder effectiveness was increased by power and was not symmetrical about zero yaw (fig. 16). About -5° rudder deflection was required to trim the model at zero yaw for the climb condition of figure 16.

DISCUSSION

Effect of power on characteristics in pitch.- The component effects of power on aerodynamic characteristics of single-engine tractor monoplanes are described and methods are given for their evaluation in reference 1. A brief discussion of power effects, induction effects due to the slipstream boundaries being neglected, follows:

The direct effect of the propeller forces may be considered separately as the effect of the thrust force and of the normal force. As the thrust axis does not usually pass through the center of gravity, the thrust produces a pitching moment about the center of gravity. This pitching moment increases with lift coefficient for constant power operation because the thrust coefficient increases with lift coefficient. If the thrust axis is above the center of gravity, the resulting moments will be stabilizing. The propeller normal force also produces a pitching moment about the center of gravity because it acts in the plane of the propeller. This pitching moment is destabilizing for the conventional tractor arrangement. Roughly, half of the total increment of pitching moment given in figure 7 is due to the direct effect of the normal force. The decrease in the slope of the pitching-moment curve with increase in blade angle illustrated in figure 10(a) is caused by the change in normal force with blade angle, but this effect is partly masked by the changes in slipstream distortion also associated with changes in blade angle.

The slipstream may be broken into components of axial velocity, normal velocity, and angular velocity. The axial velocity results in an increase in the dynamic pressure over the wing, the fuselage, and the tail, thus increasing the various aerodynamic forces and moments of these parts. With the flap neutral, the change in wing pitching moment due to the axial velocity is usually negligible. With flaps deflected, however, the change is often large enough to make the model without tail stable for full-rated-power conditions. This condition results from the fact that, although the models with flaps deflected and without tail are unstable, power off, the pitching moments are usually negative. The slipstream then increases these negative moments. The increase is greater in the high-lift range than in the low-lift range because the slipstream velocity ratio increases with lift coefficient for constant-power operation.

The axial velocity of the slipstream increases the elevator and stabilizer effectiveness, provided that the slipstream passes over the tail surface. The change of velocity at the tail with lift coefficient is destabilizing if the tail lift is negative (down) and stabilizing if the tail lift is positive (up). The destabilizing downwash at the tail is increased by the axial component of the inclined slipstream. It may be noted that for cases where the tail surfaces have a destabilizing effect $\left(\frac{d\epsilon}{d\alpha} > 1\right)$, an increase in tail area will increase the instability.

The velocity normal to the slipstream axis increases the downwash at the tail. Approximately half of the calculated total increment of pitching moment due to the propeller normal-force effect, as shown in figure 7, is due to the increased downwash caused by the normal force.

The angular velocities in the slipstream do not seem to have a very large direct effect on pitching moment because they increase the downwash on half of the wing and tail by about the amount that they decrease the downwash on the other half. Of course, the wing distorts the slipstream in such a way that the angular-velocity distribution at the tail is by no means perfectly symmetrical. Thus, the effect of the angular velocities upon the pitching moments will depend in a large measure upon the way the slipstream is distorted by the wing.

Effect of power on characteristics in yaw.- The changes in the lateral characteristics due to power will be considered in two parts: first, the changes caused by the propeller forces, and second, the changes caused by the resulting slipstream. The direct effect of the propeller forces and moments may be broken into components of thrust, normal force (force parallel to Y axis), and torque. For the usual single-engine tractor airplane, the thrust axis and the center of gravity lie in the plane of symmetry and, as a result, the thrust forces have no effect on the rolling or the yawing moments (about the stability axes). The propeller normal force lies in the plane of the propeller and therefore produces a yawing moment about the center of gravity. The magnitude of the yawing moment depends upon the propeller-operating condition but is always destabilizing for tractor airplanes. The reaction of the propeller torque is transmitted to the airplane and causes a moderate rolling moment and a small yawing moment about the stability axes.

The increase in dynamic pressure over the vertical tail surfaces causes an increase in rudder effectiveness with power when the tail is in the slipstream. As the angle of yaw is increased, the tail surfaces pass out of the slipstream and the rudder effectiveness is decreased to the power-off value. Because of the deformation of the slipstream due to the wing (reference 14), the tail usually moves out of the slipstream sooner when yawed positively than when yawed negatively (for right-hand propeller operation) and the variation of rudder effectiveness with yaw is not symmetrical about zero yaw (fig. 16).

The increase in dynamic pressure over the fuselage and tail surfaces contributes to the changes in pitching moment due to yaw. The decrease in the effective dihedral caused by power is believed to be partly due to the fact that, when the airplane is yawed, the slipstream is deflected over the trailing-wing panel and increases the dynamic pressure and, consequently, the lift of the trailing wing. This increased trailing-wing lift (and decreased leading-wing lift) results in a rolling moment that increases with angle of yaw but is of opposite sign to the normal (desirable) dihedral effects. This difference in the dynamic pressure upon the two sides of the wing panel also contributes to the yawing moment due to yaw. The position of the center of pressure of the vertical tail with respect to the X axis determines the influence of the increased tail effectiveness upon the dihedral effect.

Although it has not been definitely established, it is thought that the effect of wing-fuselage interference upon the rolling and yawing moments due to yaw (reference 15) may be increased by the increased dynamic pressure of the slipstream. Thus, the adverse effects of interference on the effective dihedral of low-wing monoplanes would be increased and the favorable effects of the interference for high-wing monoplanes would also be increased. The same reasoning indicates that the favorable interference upon weathercock stability of low-wing monoplanes would be increased, and the unfavorable interference of high-wing monoplanes would also be increased. Because the sidewash angles at the tail are determined as a vector addition of the various components of air flow due to the wing, the fuselage, and the slipstream, the axial velocity has a rather large direct influence upon the sidewash angles of the tail.

The velocities normal to the axis contribute toward the sidewash angles of the air flow passing over the wing, the fuselage, and the tail. One of the effects of the sidewash at the wings is to resist the undesirable displacement of the slipstream, which decreases the effective dihedral. The sidewash at the fuselage and at the tail surfaces changes the angle of attack of the fuselage and the tail surfaces and thus decreases the slope of the yawing-moment curve.

The rotational velocities in the slipstream alter the angle-of-attack distribution of that portion of the wing immersed in the slipstream and thereby produce a rolling moment. The rotational velocities over the wing and the fuselage, together with the increased dynamic pressure in the slipstream, produce rather powerful yawing moments. The power-on yawing-moment curve obtained without tail surfaces is usually markedly unstable, is unsymmetrical about zero yaw, and has a larger negative yawing moment at zero yaw. The yawing moment at zero yaw is usually increased negatively by the tail surfaces for full-power operation even though the vertical tail is offset 1° or 2°. These rotational velocities account in a large measure for the effects of changes in propeller-blade angles.

CONCLUSIONS

Power had a considerable influence on both the longitudinal- and lateral-stability and the control characteristics. On single-engine, low-wing models, power decreased the longitudinal stability and the effective dihedral. The directional stability and the rudder and elevator effectiveness were usually increased by power.

Power-off tests of models may give results that are misleading with regard to the static stability of the full-scale airplane; whereas power-on tests give results that are in close agreement with flight tests.

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APPENDIX

COEFFICIENT AND SYMBOLS

C_{D_R} resultant-drag coefficient $\left(\frac{D_R}{qS}\right)$

C_Y lateral-force coefficient $\left(\frac{Y}{qS}\right)$

C_L lift coefficient $\left(\frac{Lift}{qS}\right)$

C_l rolling-moment coefficient about center of gravity $\left(\frac{L}{qSb}\right)$

C_m pitching-moment coefficient about center of gravity $\left(\frac{M}{qSc}\right)$

C_n yawing-moment coefficient about center of gravity $\left(\frac{N}{qSb}\right)$

C_{h_e} elevator hinge-moment coefficient $\left(\frac{H_e}{qS_ec_e}\right)$

C_{h_r} rudder hinge-moment coefficient $\left(\frac{H_r}{qS_rc_r}\right)$

T_c effective thrust disk-loading coefficient $\left(\frac{T_e}{\rho V^2D^2}\right)$

T_c' effective thrust coefficient $\left(\frac{T_e}{qS}\right)$

Q_c torque coefficient $\left(\frac{Q}{\rho V^2D^3}\right)$

N_c propeller normal-force coefficient $\left(\frac{\text{normal force}}{\rho V^2D^2}\right)$

C_T thrust coefficient $\left(\frac{T_e}{\rho n^2D^4}\right)$

C_P power coefficient $\left(\frac{\text{engine power}}{\rho n^3D^5}\right)$

where

D_R resultant drag, positive when directed backward

Y lateral force, positive when directed to right

L rolling moment about X axis, positive when it tends to depress right wing

M pitching moment about Y axis, positive when it tends to depress tail

N yawing moment about Z axis, positive when it tends to retard right wing

H_e elevator hinge moment, positive downward

H_r rudder hinge moment, positive toward left

q dynamic pressure $\left(\frac{1}{2} \rho V^2\right)$ (4.09 lb/sq ft)

S wing area (9.44 sq ft)

c mean aerodynamic chord (1.36 ft)

b wing span (7.46)

S_e elevator area back of hinge (0.621 sq ft)

S_r rudder area back of hinge (0.471 sq ft)

c_e root mean square elevator chord (0.284 ft)

c_r root mean square rudder chord (0.403 ft)

T_e effective thrust, lb

Q engine torque

ρ mass density of air, slugs/cu ft

V airspeed, ft/sec

D propeller diameter (2.0 ft)

n propeller speed, rps

and

α angle of attack of thrust line, deg

$\frac{d\epsilon}{d\alpha}$ rate of change of downwash angle with angle of attack

ψ angle of yaw, positive when nose of model moves to right, deg

i_t angle of stabilizer setting with respect to thrust line, positive with trailing edge down, deg

δ_e elevator deflection with respect to stabilizer chord, positive when trailing edge of elevator is moved down, deg

δ_r rudder deflection, positive when trailing edge of rudder is moved to left, deg

δ_f flap deflection, positive when trailing edge of flap is moved down, deg

δ_a aileron deflection, positive when trailing edge of aileron is moved down (subscripts R and L denote right and left ailerons), deg

V/nD advance-diameter ratio

β angle of propeller-blade setting measured at three-quarter radius

N number of blades

K constant (determined from fig. 4, reference 1) for a three-blade propeller

θ angle of climb of airplane, deg

c_p chord of propeller blade element

r radius to blade element

R propeller radius

A.F. activity factor $\left[\frac{100000}{32} \int_{0.2}^{1.0} \frac{c_p}{R} \left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)\right]$

$K_{A.F.}$ activity-factor ratio $\frac{C_{P_{(chart)}}}{C_{P_{(actual)}}}$

W airplane weight

The subscript L.F. indicates level-flight conditions.

REFERENCES

1. Goett, Harry J., and Pass, H. R.: Effect of Propeller Operation on the Pitching Moments of Single-Engine Monoplanes. NACA A.C.R., May 1941.

2. Millikan, Clark B.: The Influence of Running Propellers on Airplane Characteristics. Jour. of Aero. Sci., vol. 7, no. 3, Jan. 1940, pp. 85-106.

3. Donlan, C. J., and Recant, I. G.: Methods of Analyzing Wind-Tunnel Data for Dynamic Flight Conditions. T.N. No. 828, NACA, 1941.

4. Gilruth, R. R., and White, M. D.: Analysis and Prediction of Longitudinal Stability of Airplanes. Rep. No. 711, NACA, 1941.

5. Recant, I. G.: Plate Method of Ground Representation for Wind-Tunnel Determination of Elevator Effectiveness in Landing. T.N. No. 823, NACA, 1941.

6. Bamber, M. J., and House, R. O.: Wind-Tunnel Investigation of Effect of Yaw on Lateral-Stability Characteristics. I - Four NACA 23012 Wings of Various Plan Forms with and without Dihedral. T.N. No. 703, NACA, 1939.

7. Zimmerman, Charles H.: An Analysis of Lateral Stability in Power-Off Flight with Charts for Use in Design. Rep. No. 589, NACA, 1937.

8. Jones, Robert T.: The Influence of Lateral Stability on Disturbed Motions of an Airplane with Special Reference to the Motions Produced by Gusts. Rep. No. 638, NACA, 1938.

9. Jones, Robert T., and Cohen, Doris: An Analysis of the Stability of an Airplane with Free Controls. Rep. No. 709, NACA, 1941.

10. Biermann, David, and Hartman, Edwin P.: Tests of Five Full-Scale Propellers in the Presence of a Radial and a Liquid-Cooled Engine Nacelle, Including Tests of Two Spinners. Rep. No. 642, NACA, 1938.

11. Hartman, Edwin P., and Biermann, David: The Negative Thrust and Torque of Several Full-Scale Propellers and Their Application to Various Flight Problems. Rep. No. 641, NACA, 1938.

12. Harris, Thomas A.: The 7 by 10 Foot Wind Tunnel of the National Advisory Committee for Aeronautics. Rep. No. 412, NACA, 1931.

13. Wenzinger, Carl J., and Harris, Thomas A.: Wind-Tunnel Investigation of an NACA 23012 Airfoil with Various Arrangements of Slotted Flaps. Rep. No. 664, NACA, 1939.

14. Katzoff, S.: Longitudinal Stability and Control with Special Reference to Slipstream Effects. Rep. No. 690, NACA, 1940.

15. House, Rufus O., and Wallace, Arthur R.: Wind-Tunnel Investigation of Effect of Interference on Lateral-Stability Characteristics of Four NACA 23012 Wings, an Elliptical and a Circular Fuselage, and Vertical Fins. Rep. No. 705, NACA, 1941.

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TABLE I. - TESTS REQUIRED FOR DETERMINATION OF LONGITUDINAL STABILITY, CONTROL, AND TRIM

[For each test, the angle of attack covers the entire range. Each test should be made with zero values of angle of yaw, rudder deflection, rudder-tab deflection, aileron deflection, and aileron-tab deflection. Values should be read for lift, drag, pitching moment, elevator-hinge moment, and power parameters on each test]

Test	Flap condition	Landing-gear condition	Stabilizer deflection	Elevator deflection	Elevator-tab deflection	Power condition
1	Neutral	Up	a[1]	Zero	Zero	Full
2	----do----	--do---	b[1]	---do---	--do---	Do.
3	Deflected	Down	a[1]	---do---	--do---	Do.
4	----do----	--do---	b[1]	---do---	--do---	Do.
5	----do----	--do---	a[1]	---do---	--do---	Windmilling
6	----do----	--do---	b[1]	---do---	--do---	Do.
7	----do----	--do---	Trim at cruising	a[1]	--do---	Do.
8	----do----	--do---	---do---	b[1]	--do---	Do.
9	----do----	--do---	---do---	c[1]	--do---	Do.
10	----do----	--do---	---do---	a[1]	--do---	Half
11	----do----	--do---	---do---	b[1]	--do---	Do.
12	----do----	--do---	---do---	c[1]	--do---	Do.
13	----do----	--do---	---do---	a[1]	--do---	Full
14	----do----	--do---	---do---	b[1]	--do---	Do.
15	----do----	--do---	---do---	c[1]	--do---	Do.
16	Neutral	Up	---do---	a[1]	--do---	Do.
17	----do----	--do---	---do---	b[1]	--do---	Do.
18	----do----	--do---	---do---	c[1]	--do---	Do.
19	----do----	--do---	---do---	a[1]	--do---	Half
20	----do----	--do---	---do---	b[1]	--do---	Do.
21	----do----	--do---	---do---	c[1]	--do---	Do.
22	----do----	--do---	---do---	a[1]	a[1]	Do.
23	----do----	--do---	---do---	---do---	--do---	Full
24	Deflected	Down	---do---	---do---	--do---	Windmilling

[1] Values a, b, and c indicate numerical values (not zero) of deflection angles.

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TABLE II

TESTS REQUIRED FOR DETERMINATION OF STABILITY, CONTROL, AND TRIM

[For each test, the angle of yaw covers the entire range, the stabilizer is set for trim at cruising, the elevator-tab deflection is zero. Values of lift, drag, pitching moment, yawing moment, rudder-hinge moment, rolling moment, lateral force, and power parameters are read for each test. Values of elevator hinge moment are read for tests 1, 6, 11, 16, 21, and 22. Values of aileron hinge moment are read for tests 1, 11, and 25 to 32]

Test	Flap condition	Landing-gear condition	Angle of attack	Elevator deflection	Rudder deflection	Rudder-tab deflection	Aileron deflection	Power condition
1	Neutral	Up	High speed	Trim	Zero	Zero	Zero	Full
2	---do---	---do---	---do---	---do---	a[1]	---do---	---do---	Do.
3	---do---	---do---	---do---	---do---	b[1]	---do---	---do---	Do.
4	---do---	---do---	---do---	---do---	c[1]	---do---	---do---	Do.
5	---do---	---do---	---do---	---do---	d[1]	---do---	---do---	Do.
6	---do---	---do---	Climb	---do---	Zero	---do---	---do---	Do.
7	---do---	---do---	---do---	---do---	a[1]	---do---	---do---	Do.
8	---do---	---do---	---do---	---do---	b[1]	---do---	---do---	Do.
9	---do---	---do---	---do---	---do---	c[1]	---do---	---do---	Do.
10	---do---	---do---	---do---	---do---	d[1]	---do---	---do---	Do.
11	Deflected	Down	2° below power-off stall	---do---	Zero	---do---	---do---	Do.
12	---do---	---do---	---do---	---do---	a[1]	---do---	---do---	Do.
13	---do---	---do---	---do---	---do---	b[1]	---do---	---do---	Do.
14	---do---	---do---	---do---	---do---	c[1]	---do---	---do---	Do.
15	---do---	---do---	---do---	---do---	d[1]	---do---	---do---	Do.
16	---do---	---do---	---do---	---do---	Zero	---do---	---do---	Windmilling
17	---do---	---do---	---do---	---do---	a[1]	---do---	---do---	Do.
18	---do---	---do---	---do---	---do---	b[1]	---do---	---do---	Do.
19	---do---	---do---	---do---	---do---	c[1]	---do---	---do---	Do.
20	---do---	---do---	---do---	---do---	d[1]	---do---	---do---	Do.
21	---do---	---do---	---do---	Trim + a[1]	Zero	---do---	---do---	Full
22	Neutral	Up	Climb	---do---	---do---	---do---	---do---	Do.
23	---do---	---do---	---do---	Trim	---do---	a[1]	---do---	Do.
24	---do---	---do---	High speed	---do---	---do---	---do---	---do---	Do.
25	---do---	---do---	---do---	---do---	---do---	Zero	a[1]	Do.
26	---do---	---do---	---do---	---do---	---do---	---do---	b[1]	Do.
27	---do---	---do---	---do---	---do---	---do---	---do---	c[1]	Do.
28	---do---	---do---	---do---	---do---	---do---	---do---	d[1]	Do.
29	Deflected	Down	2° below power-off stall	---do---	---do---	---do---	a[1]	Do.
30	---do---	---do---	---do---	---do---	---do---	---do---	b[1]	Do.
31	---do---	---do---	---do---	---do---	---do---	---do---	c[1]	Do.
32	---do---	---do---	---do---	---do---	---do---	---do---	d[1]	Do.

[1] Values a, b, c, and d indicate numerical values (not zero) of the deflection angles.

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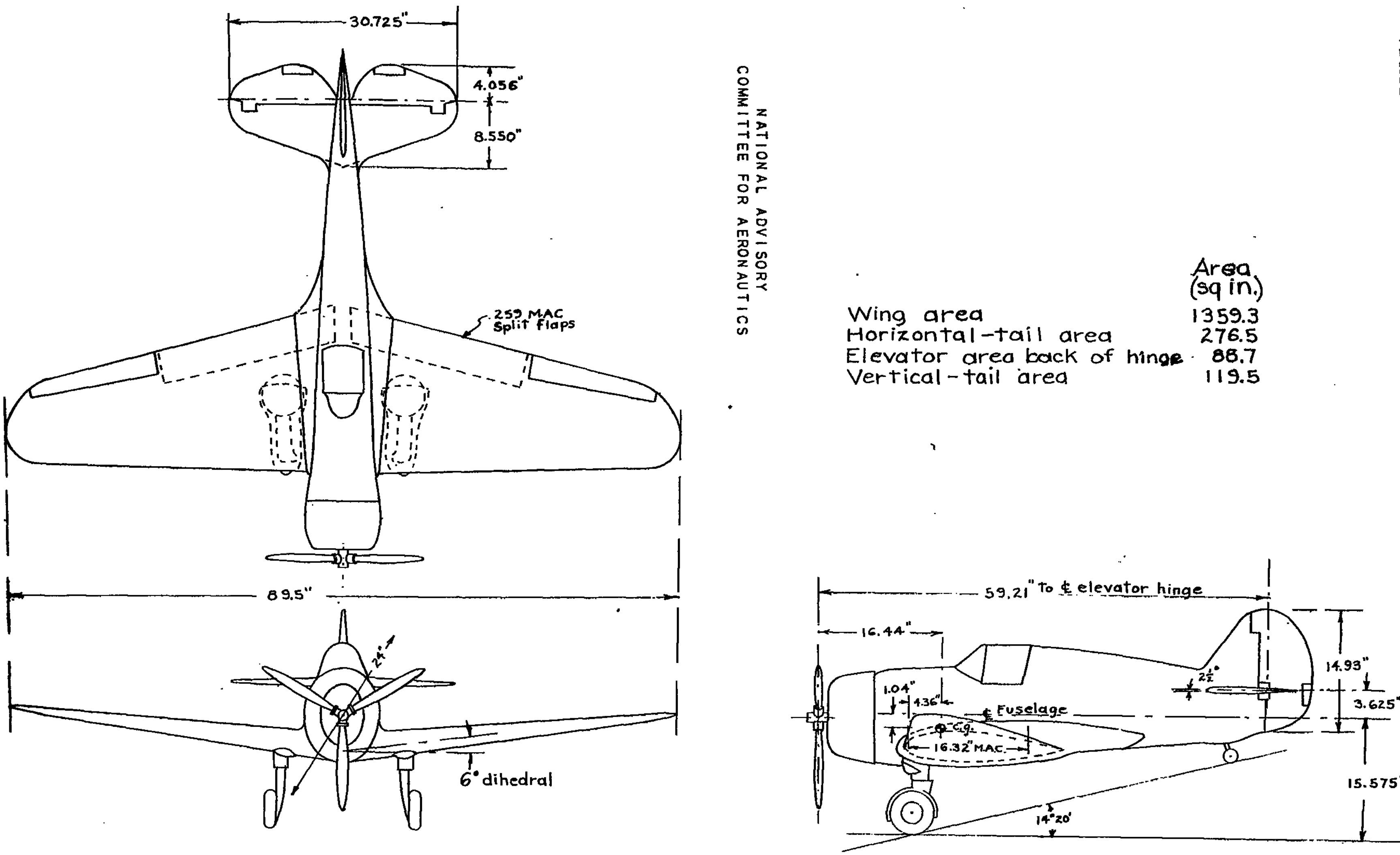

Figure 1.– Three-view drawing of the model of the single-engine low-wing monoplane for which test data are presented

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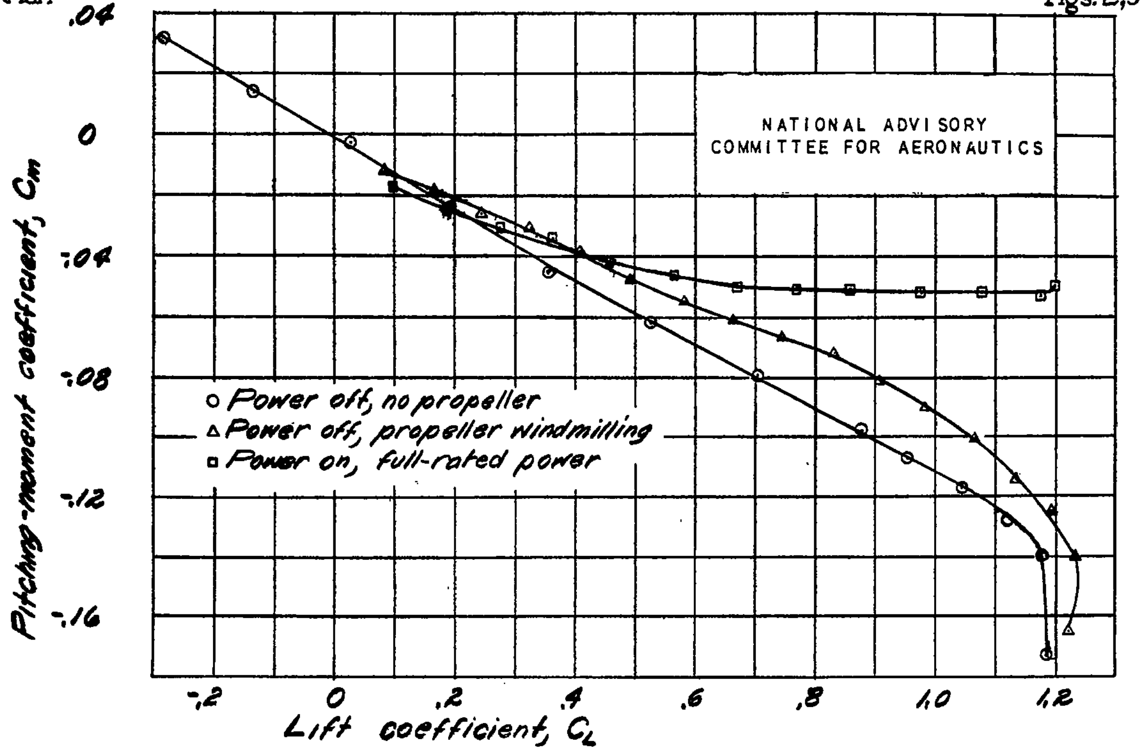

Figure 2.- Effect of propeller operation on pitching-moment coefficients. Clean model.

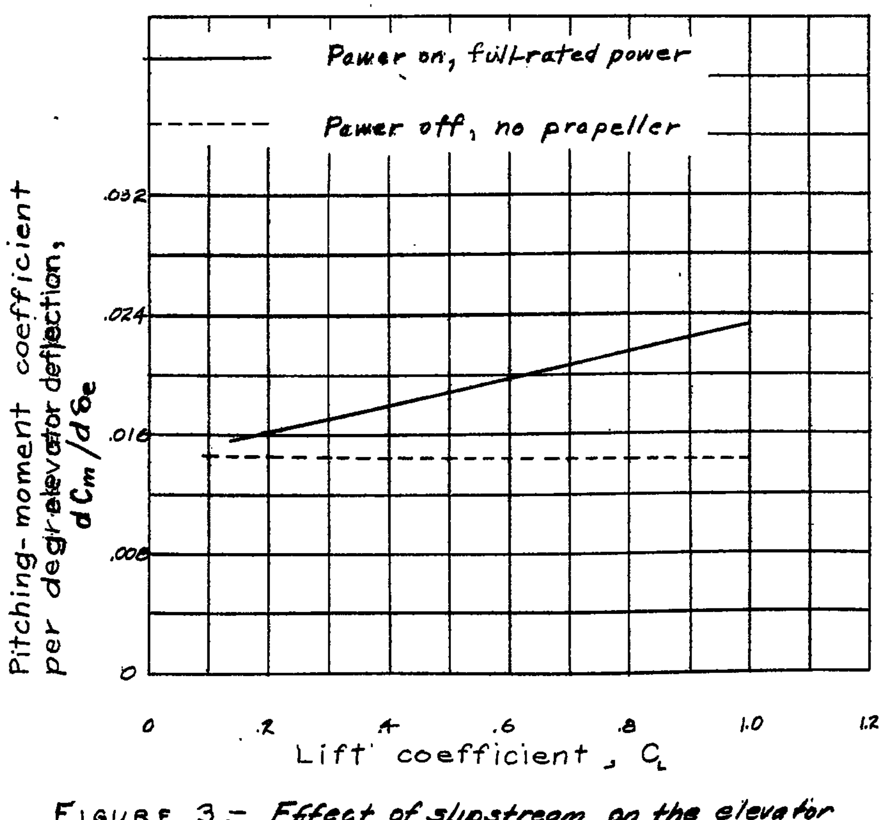

Figure 3.- Effect of slipstream on the elevator control effectiveness. Clean model.

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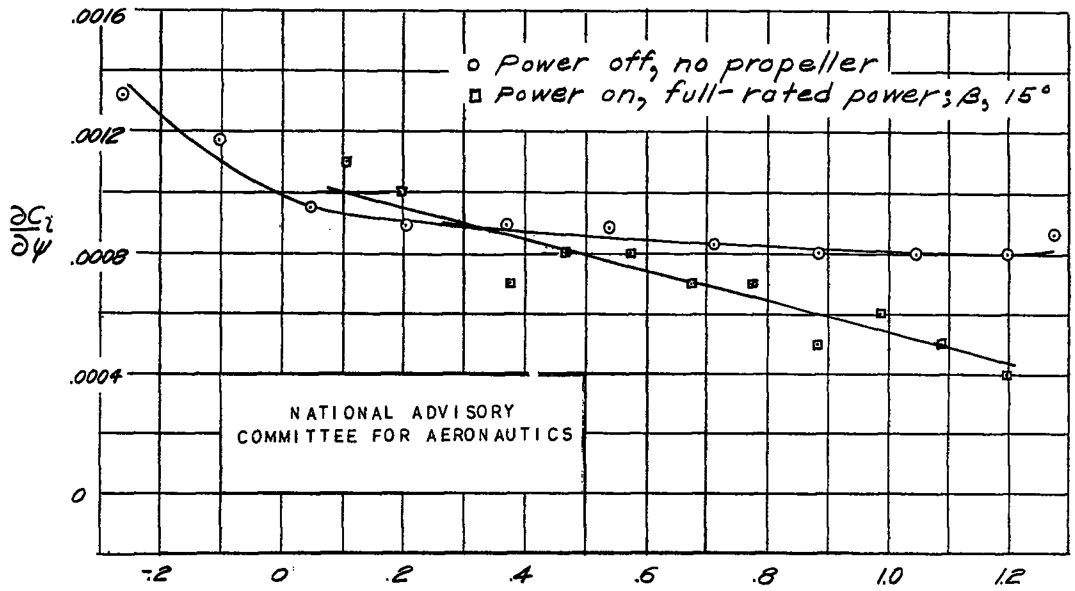

Figure 4.- Effect of propeller operation on the effective dihedral. Clean model.

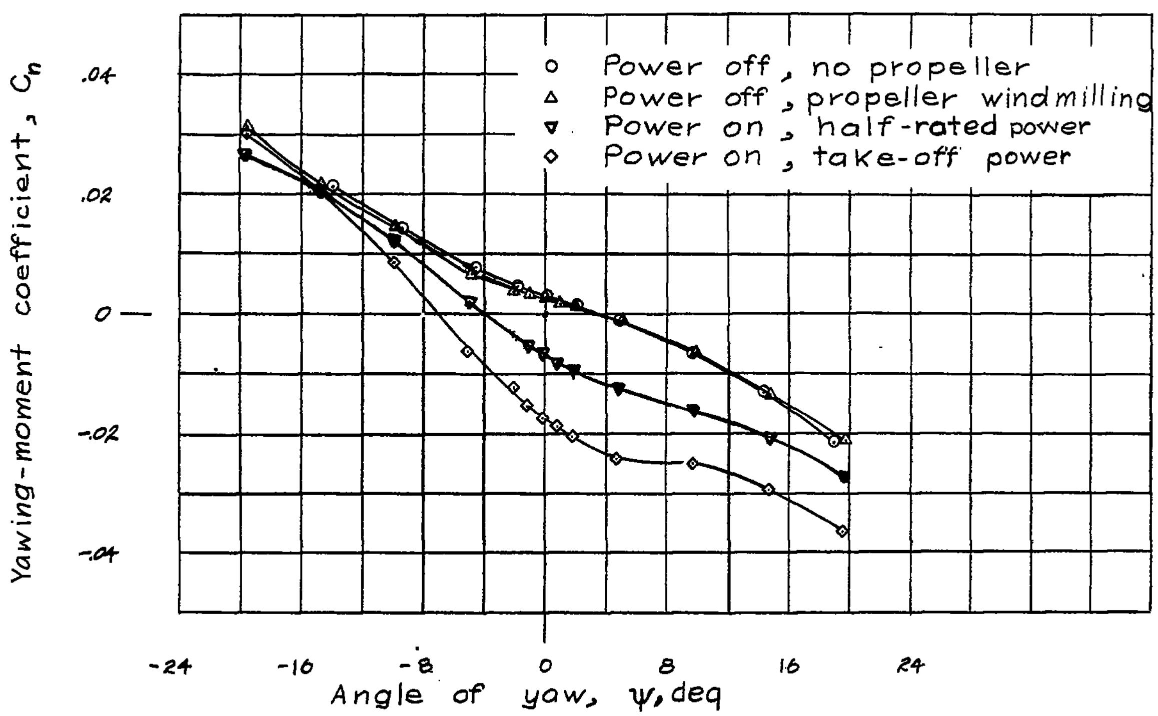

FIGURE 5.- Effect of propeller operation on yawing-moment coefficients. δ_f, 0°; α, 9.2°.

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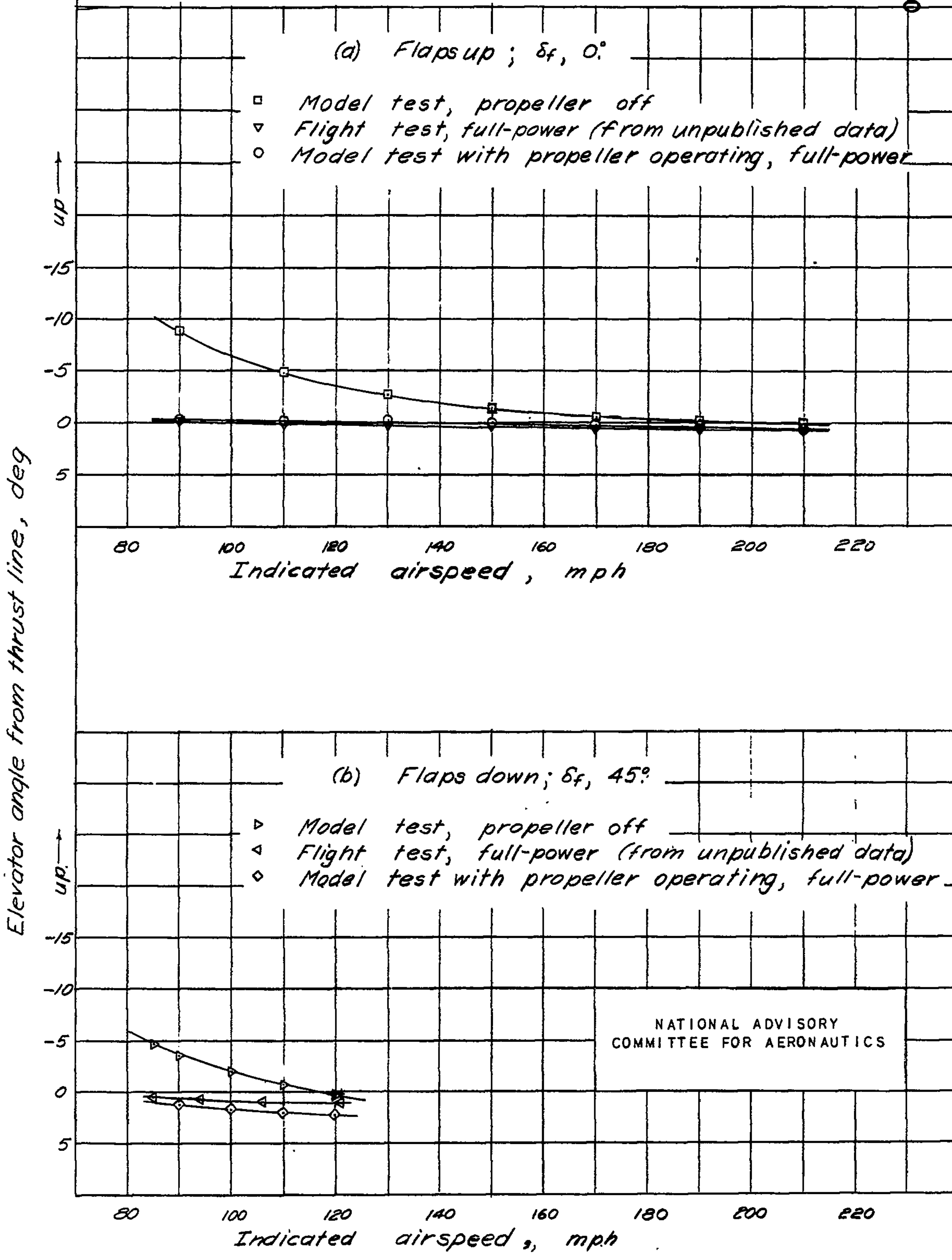

Figure 6.- Comparison of the elevator deflections required for trim for flight and for model tests. Flight test data corrected for cable stretch and tab deflection.

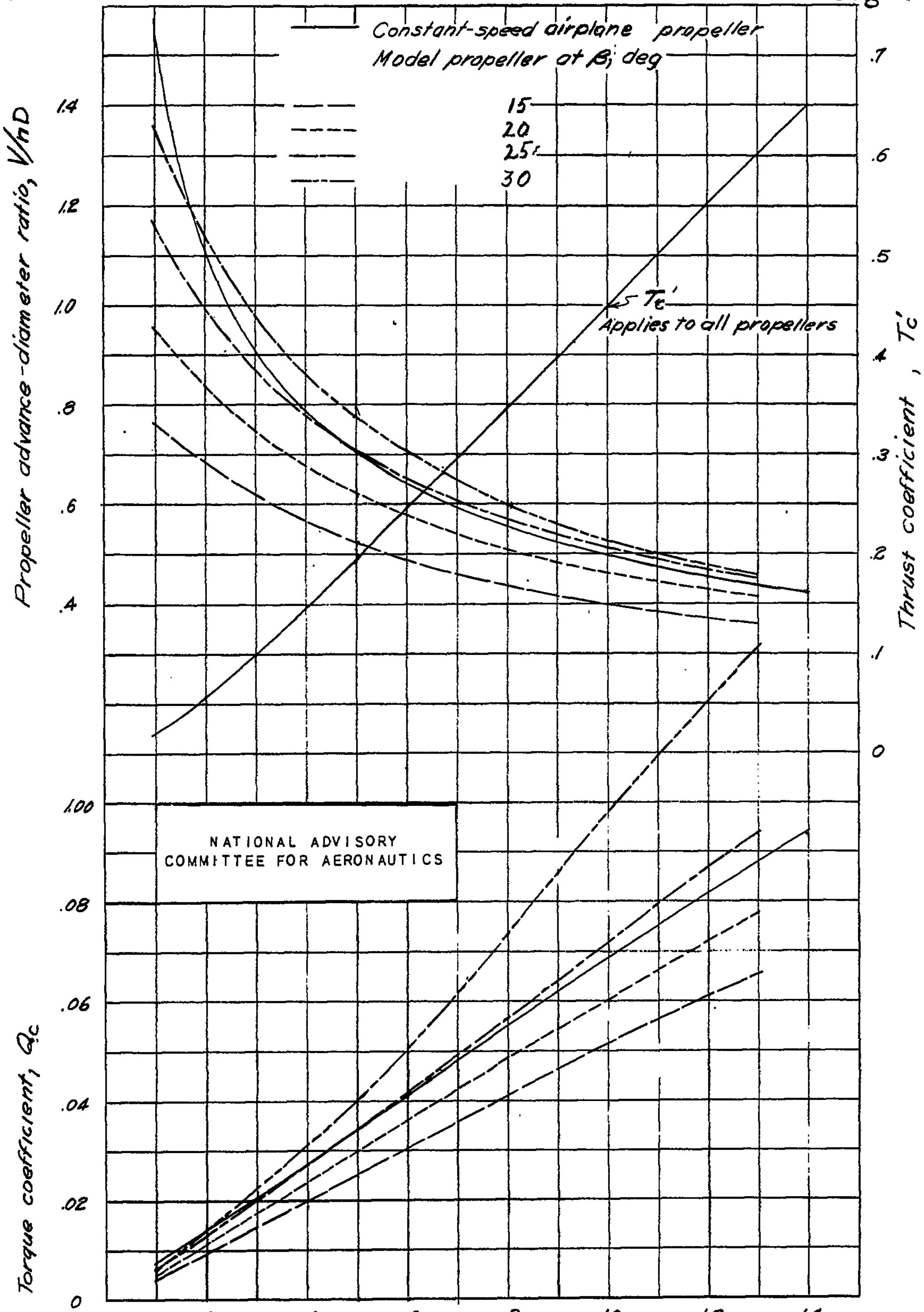

Figure 7.- Propeller characteristics and the increment of pitching-moment due to the propeller normal force as computed for the constant-speed airplane propeller (1050 hp at 1700 rpm at sea level) and for geometrically similar (fixed-pitch) model propellers at various blade angles and delivering the same thrust as the airplane.

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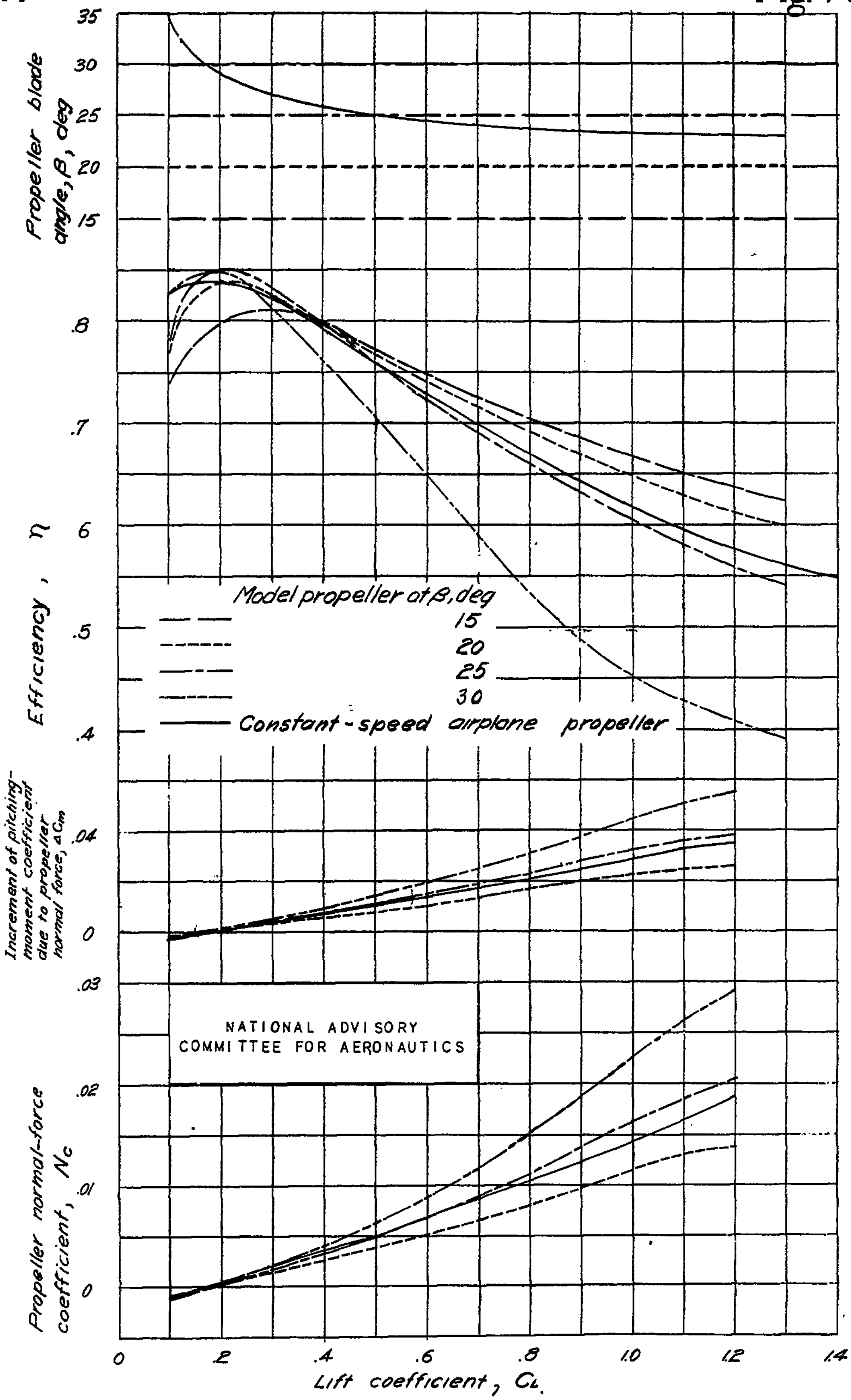

Figure 7 - Concluded.

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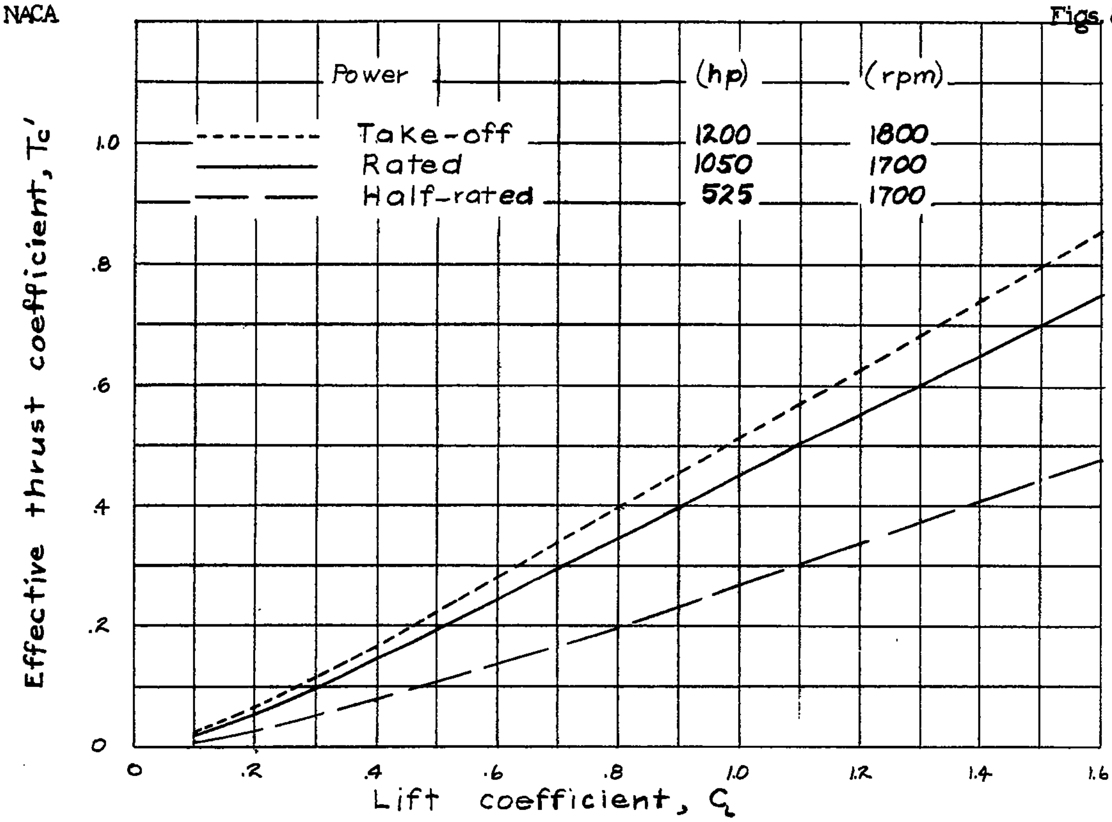

(a) Operating charts of effective thrust coefficients ($T_c' = \frac{T}{qS}$) as functions of lift coefficient for various power conditions. W, 5600 pounds; S, 236 square feet.

Figure 8.- Evolution of an operating chart.

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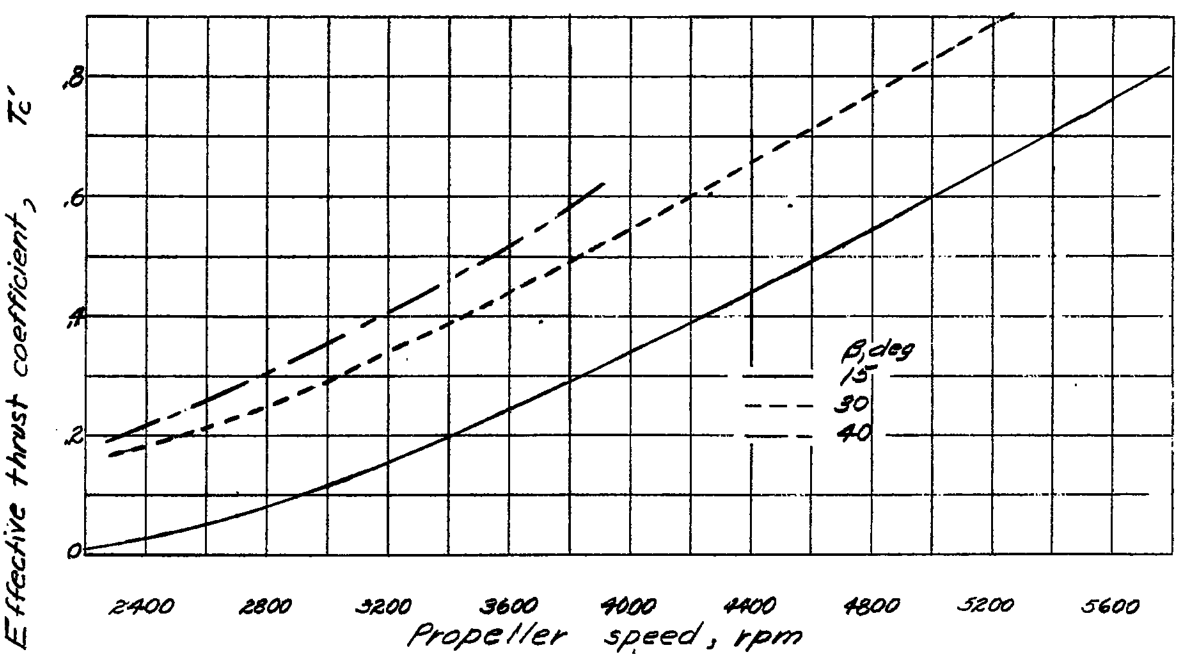

(b) Thrust calibration of model propeller; R.A.F. 6 section; α, 0°; q, 4.09 pounds per square foot; V, 59.5 feet per second; three blades; D, 2 feet.

Figure 8.- Continued.

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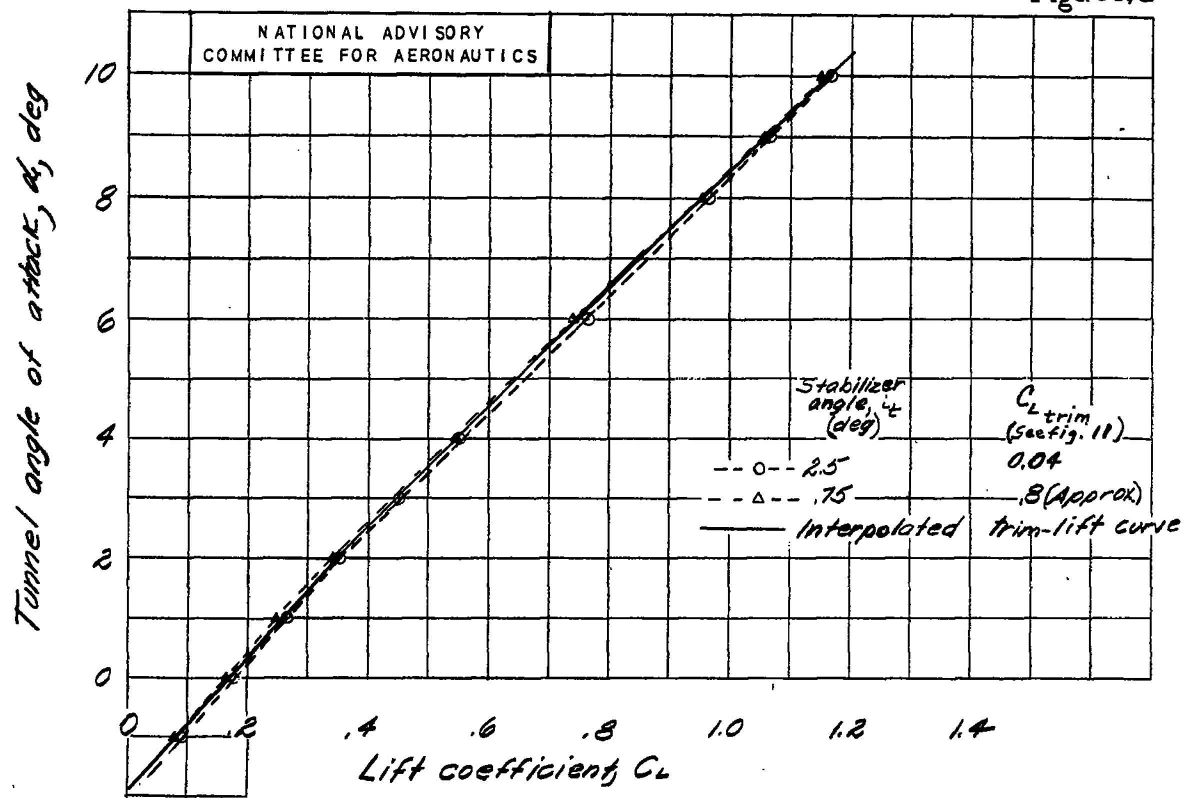
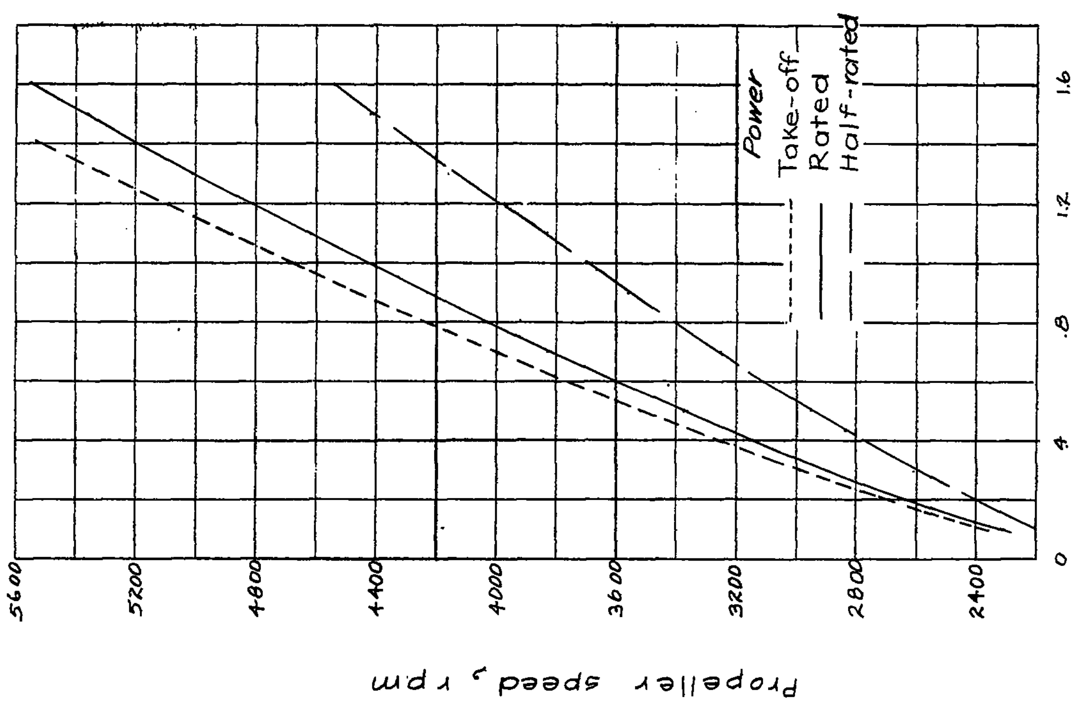


(d) Power-on trim-lift curve determined from stabilizer-angle tests. Angle of attack uncorrected for tunnel effect; full-rated power; clean model.

Figure 8.- Continued.



(c) Model propeller speed as a function of lift coefficient for various power conditions. Composite of figures 8(a) and 8(b) for $\beta = 15°$.

8.- Continued.

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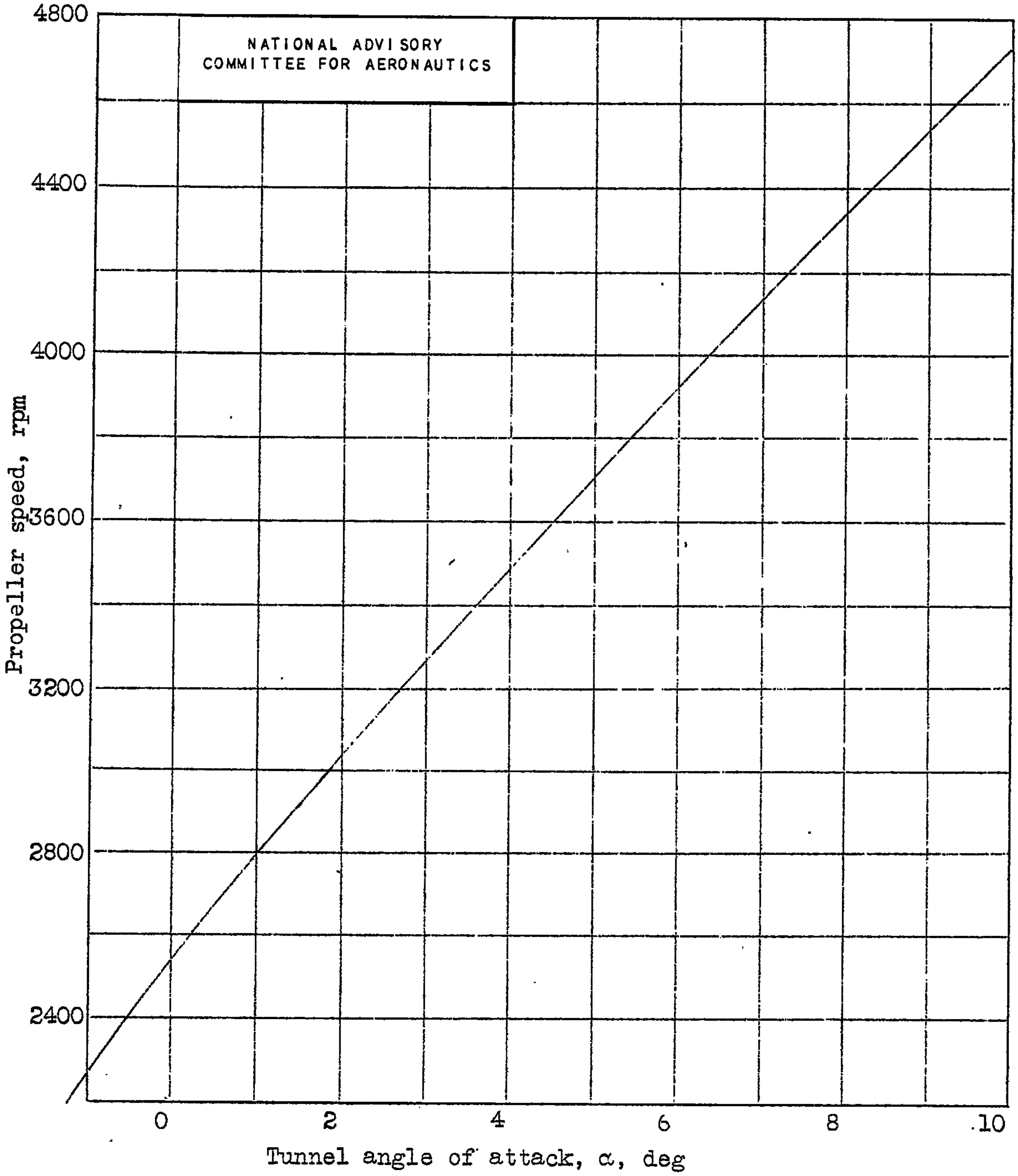

(e) Final tunnel-operating chart for the clean model; full-rated power; β, 15°.

Figure 8.- Concluded.

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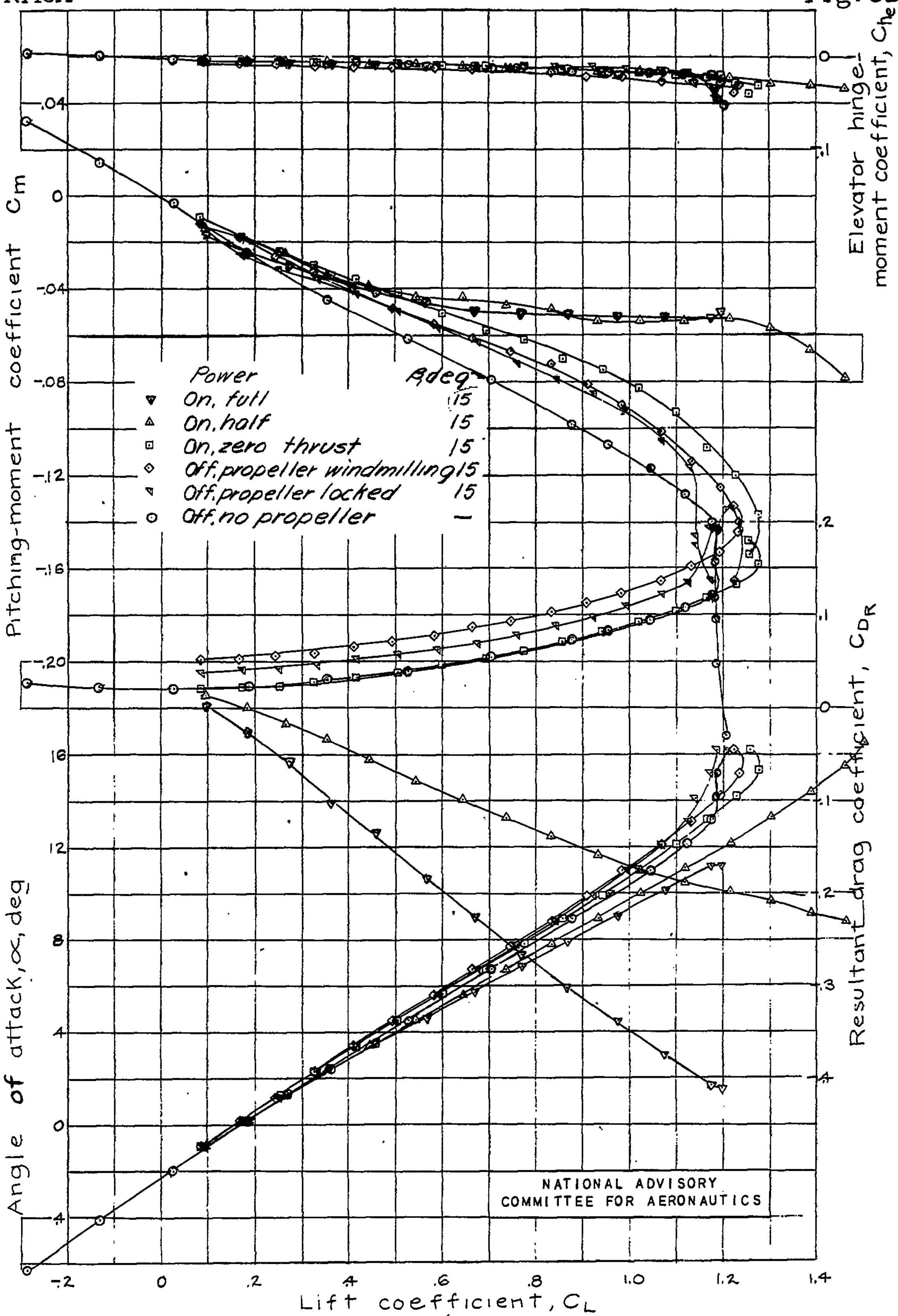
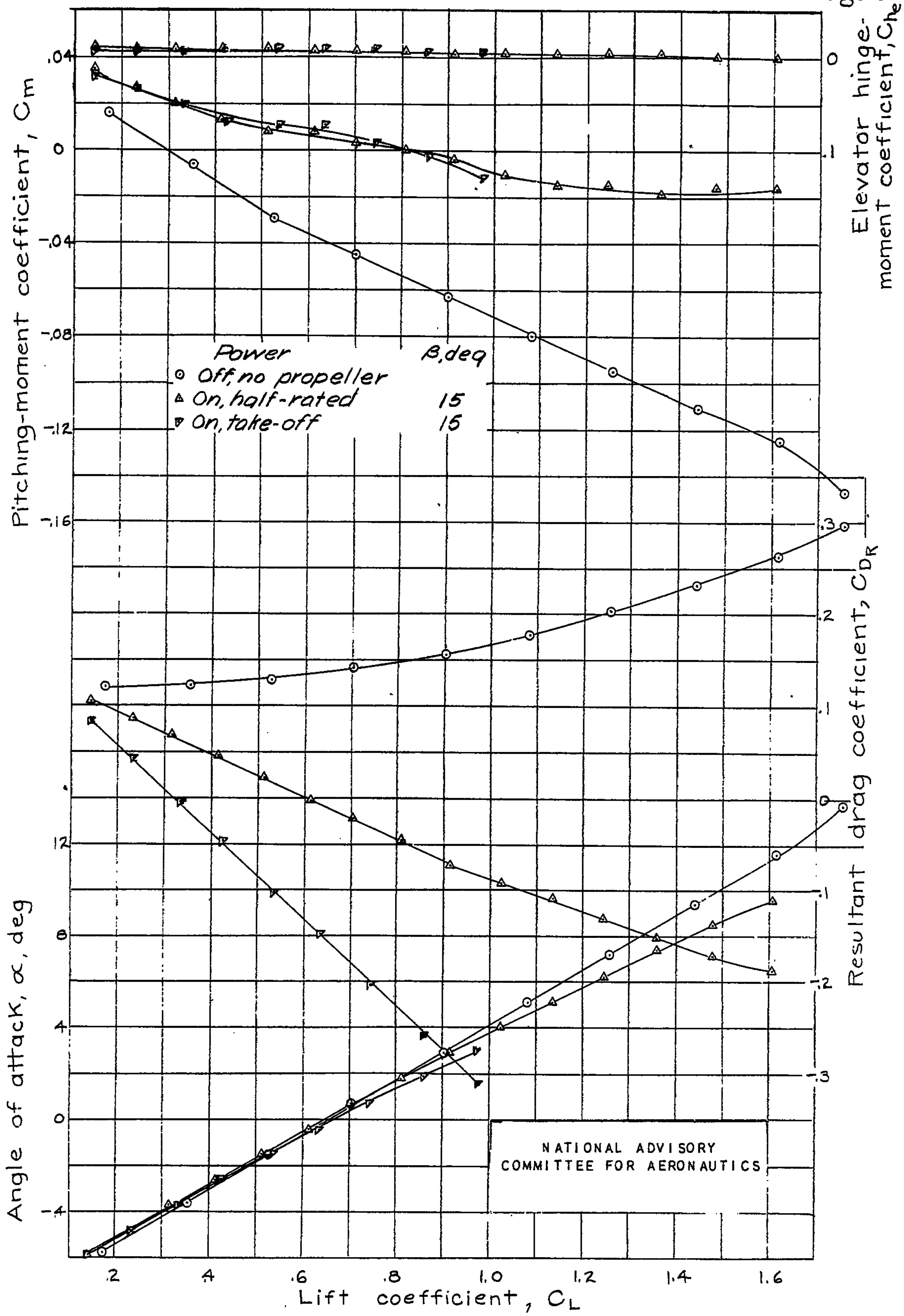
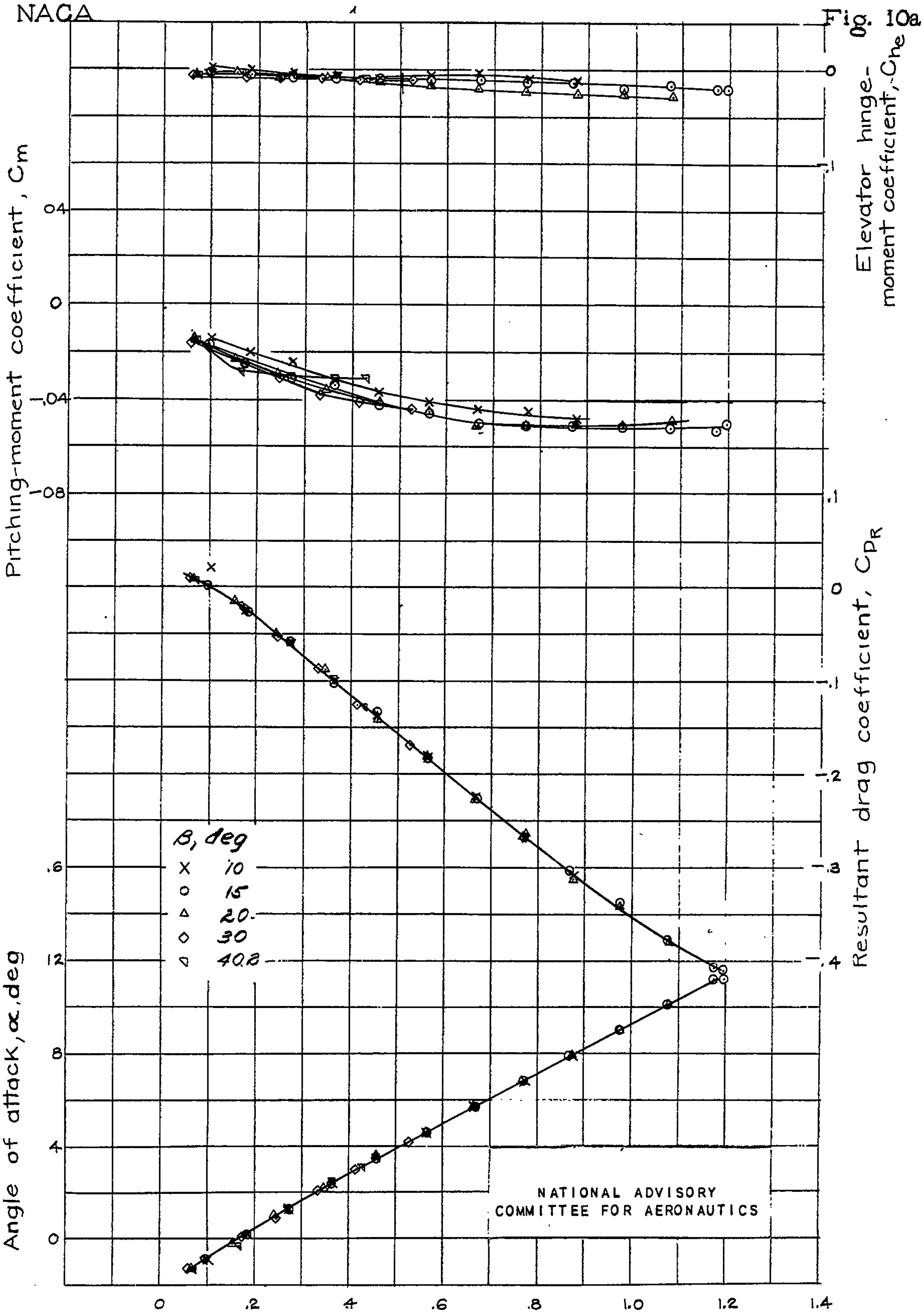


(a) Flaps neutral, landing gear up.

Figure 9.- Effect of propeller operation on the aerodynamic characteristics of the clean model in pitch.



(b) Flaps deflected, landing gear extended.



(a) Clean model with full-rated power applied.

Figure 10.—Effect of propeller blade angle on aerodynamic characteristics of the model in pitch.

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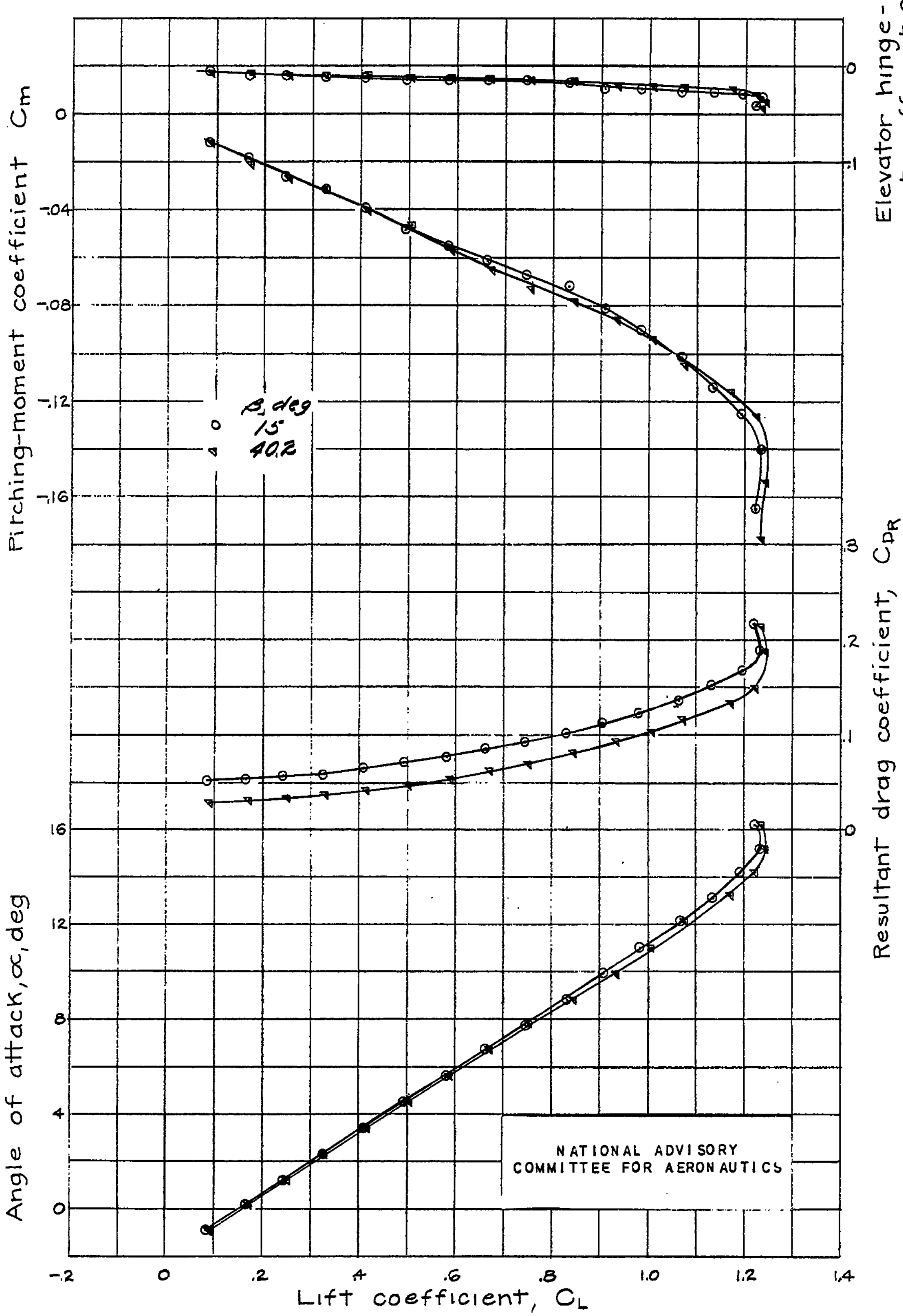

(b) Clean model with windmilling propeller.
Figure 10.- Continued.

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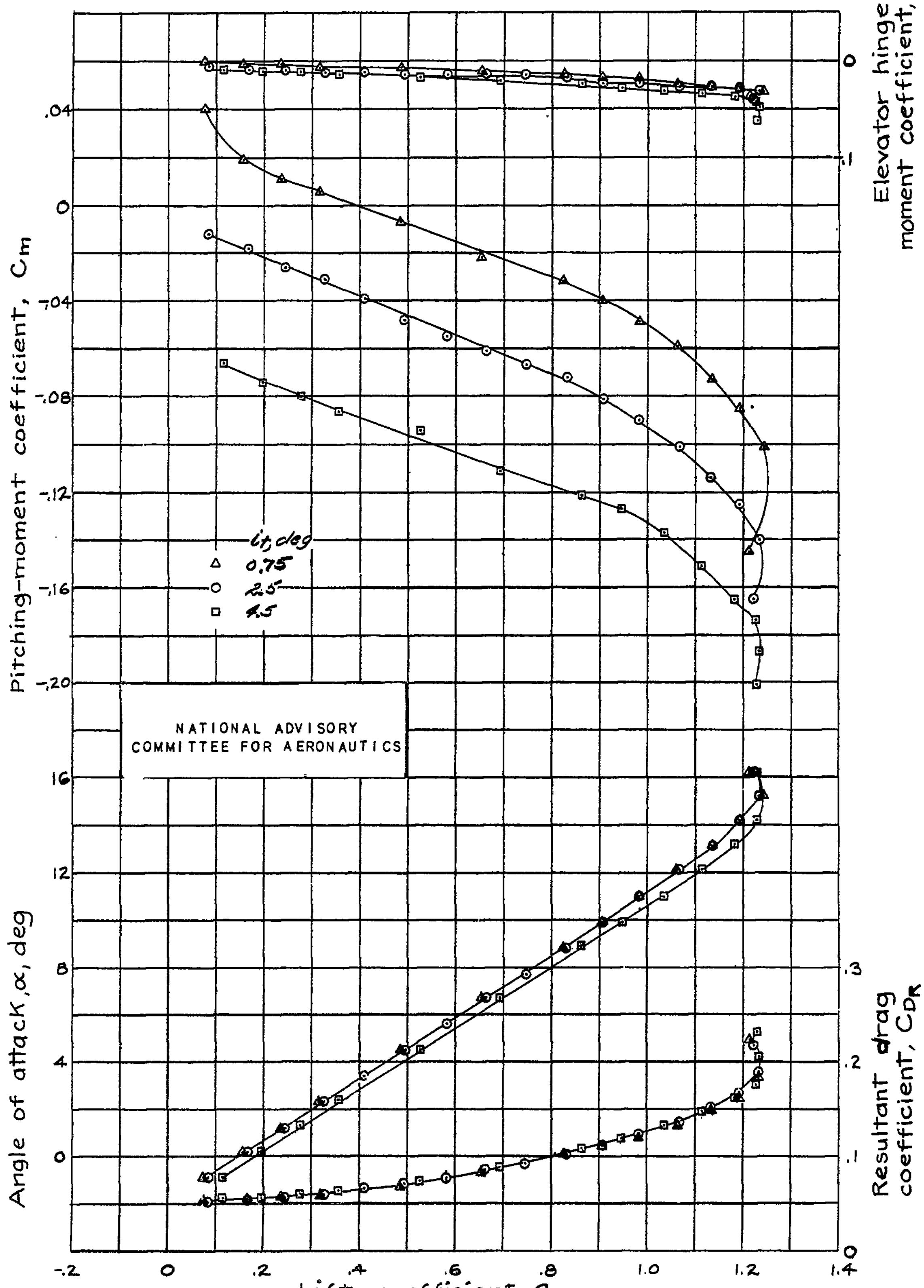

(a) Propeller windmilling; β, 15°.

Figure 11.- Effect of stabilizer angle on aerodynamic characteristics of the clean model in pitch.

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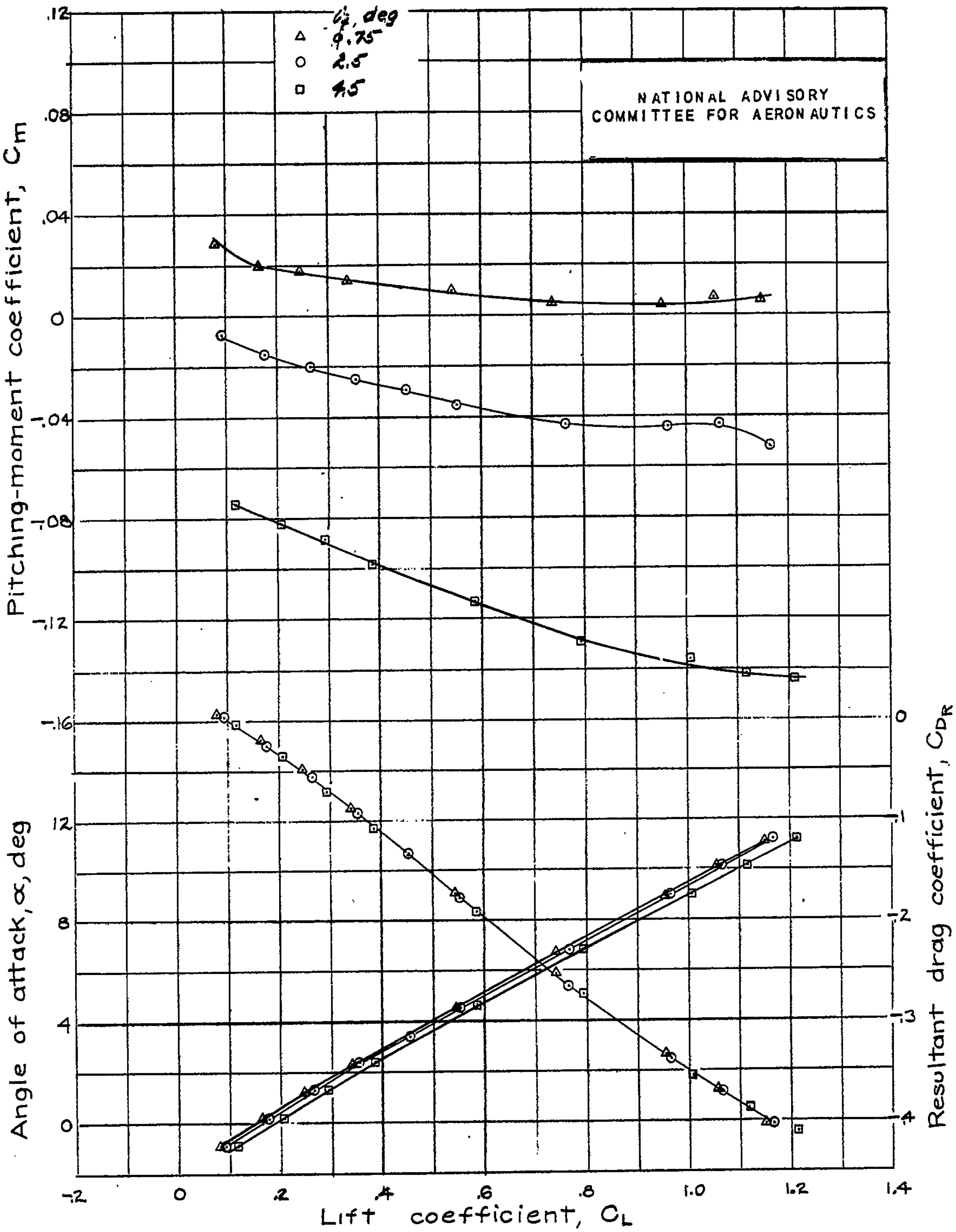

(b) Clean model with rated power; β, 15°.

Figure 11.- Concluded.

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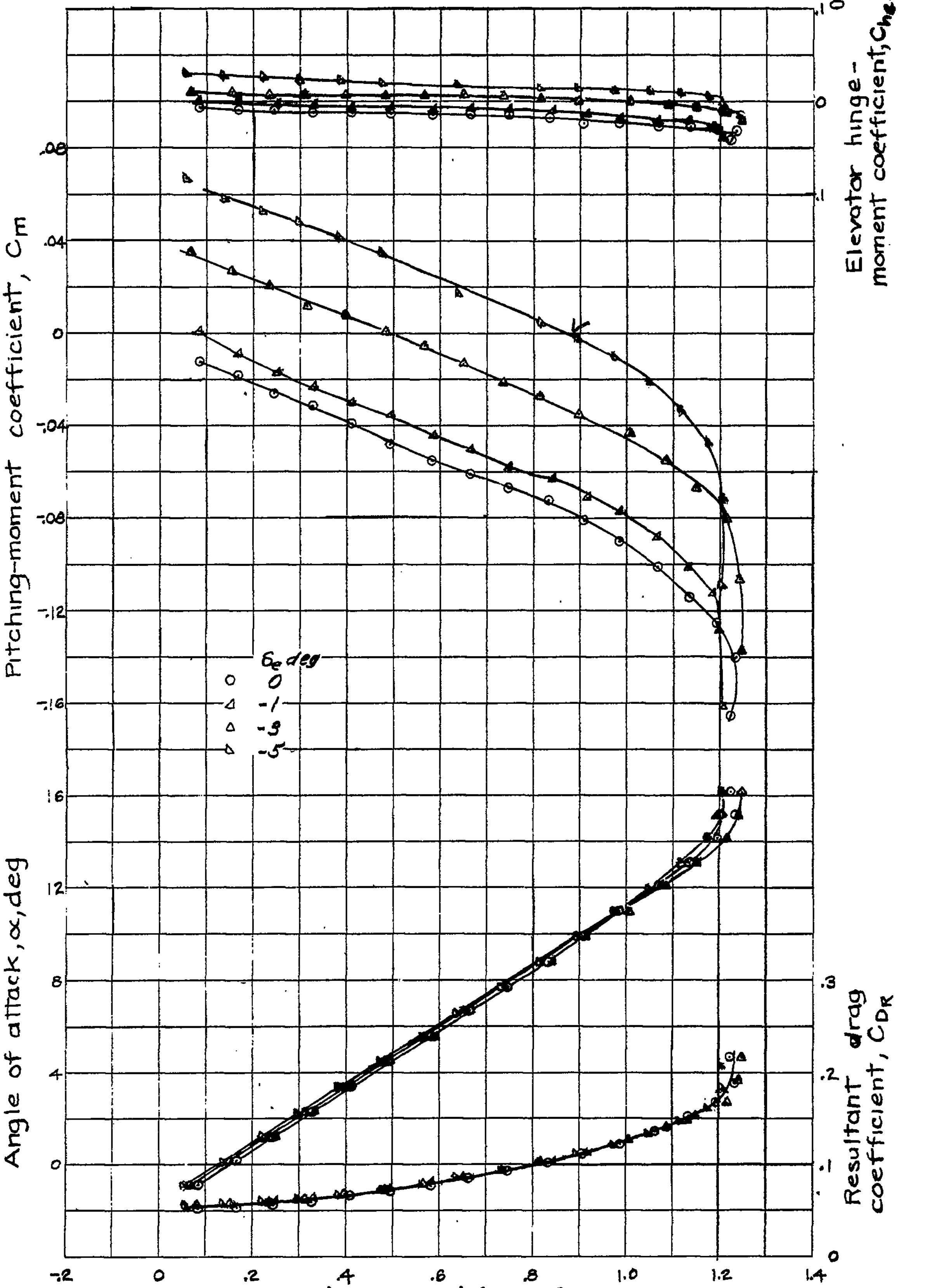

(a) Propeller windmilling; β, 15°.

Figure 12.- Effect of elevator deflection on aerodynamic characteristics of the clean model in pitch.

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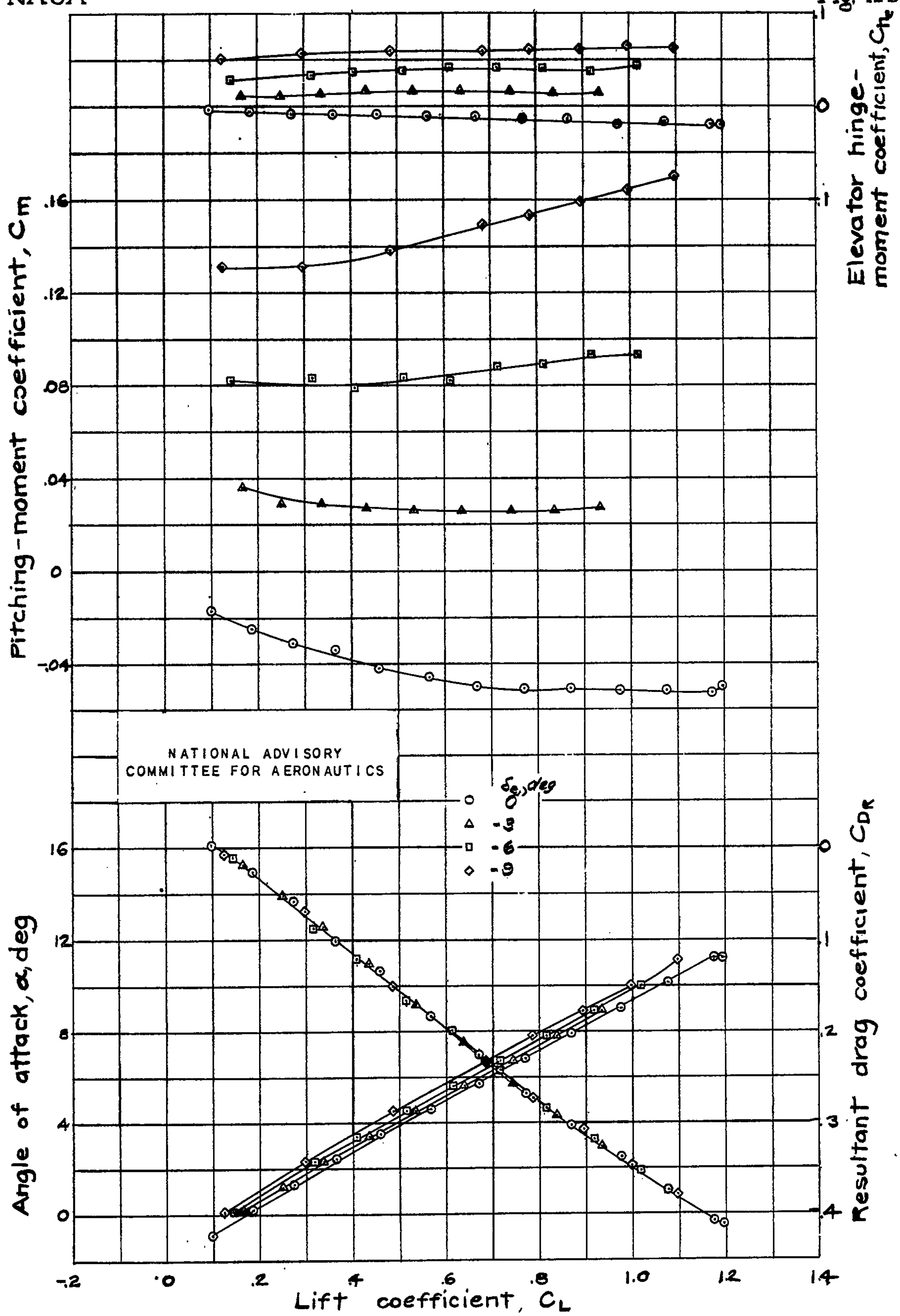

(b) Clean model with rated power; β, 15°.

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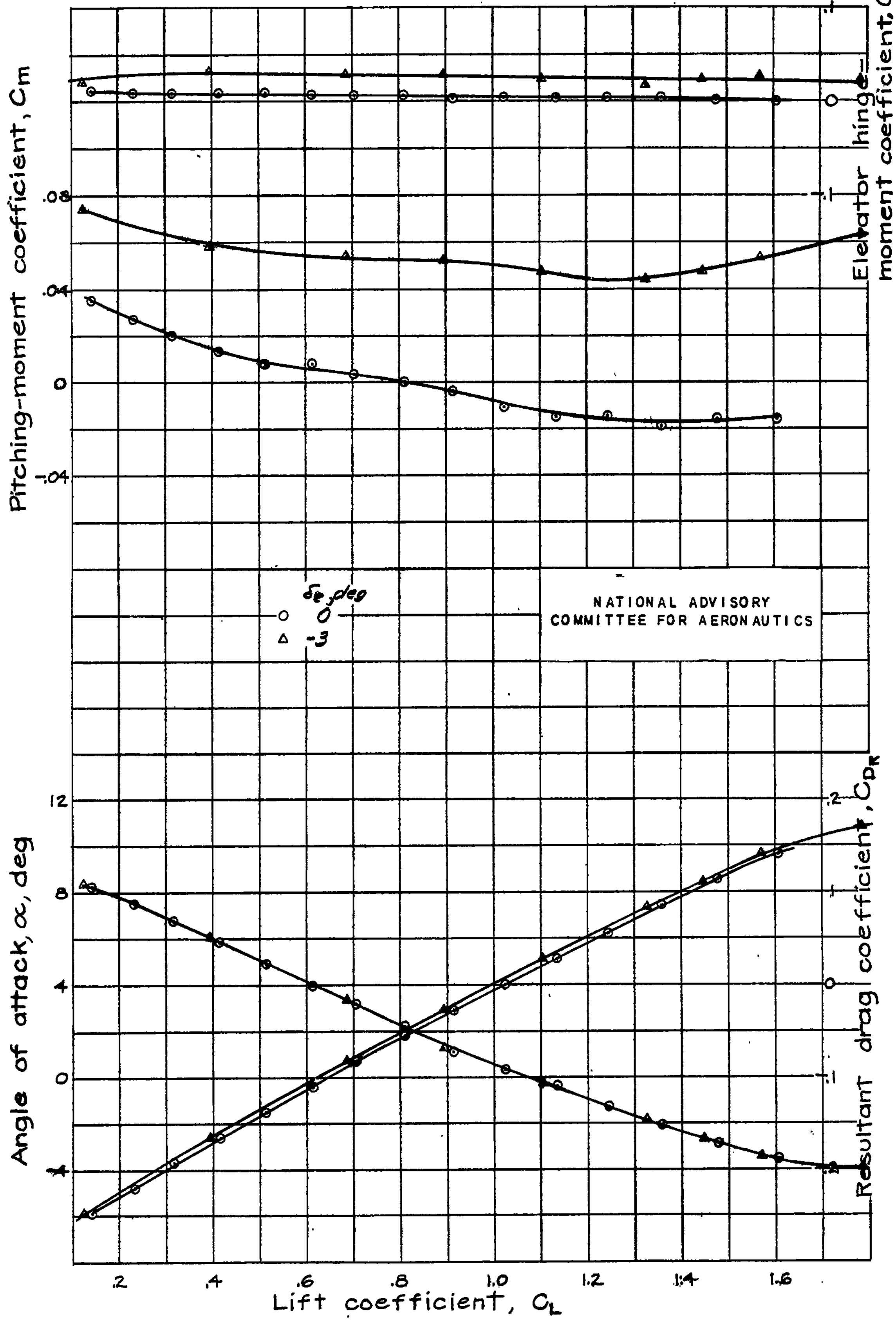

(c) Model with split flaps deflected and landing gear extended. Half rated power; β 15°.

Figure 12.- Concluded.

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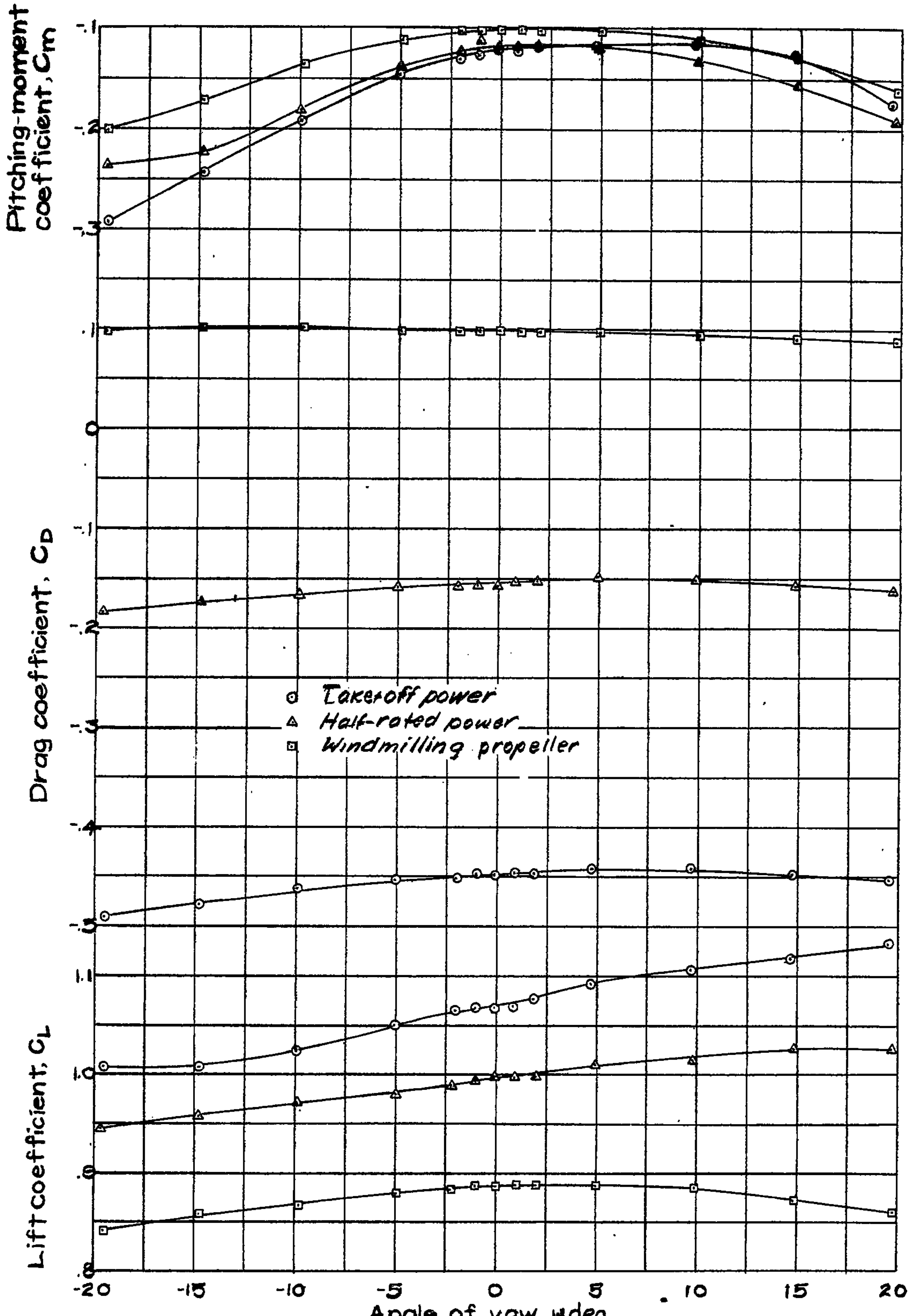

(a) Clean model in the climb attitude; β, 15°.

Figure 13.- Effect of propeller operation on the aerodynamic characteristics of the model in yaw.

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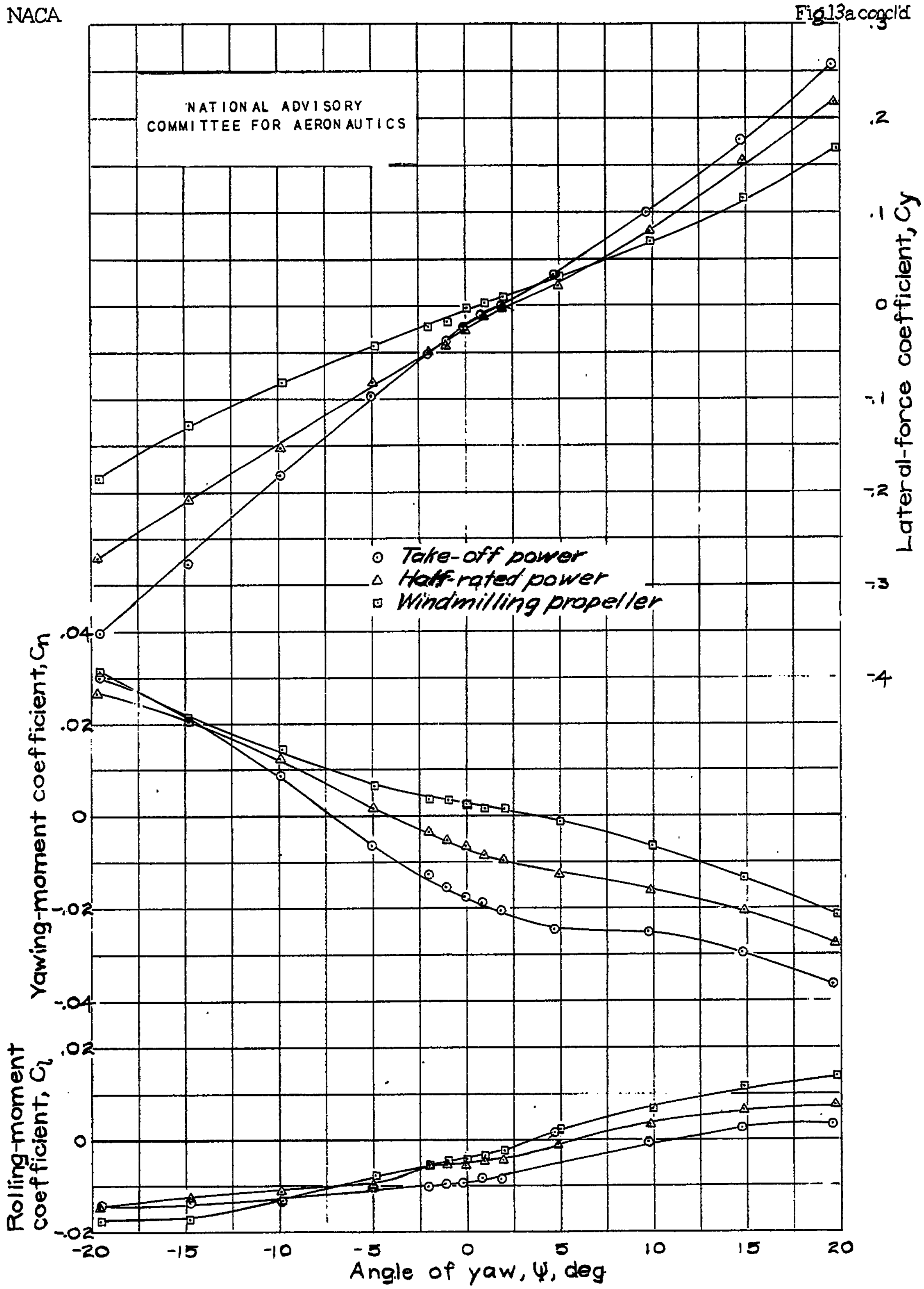

(a) Concluded.
Figure 13.- Continued.

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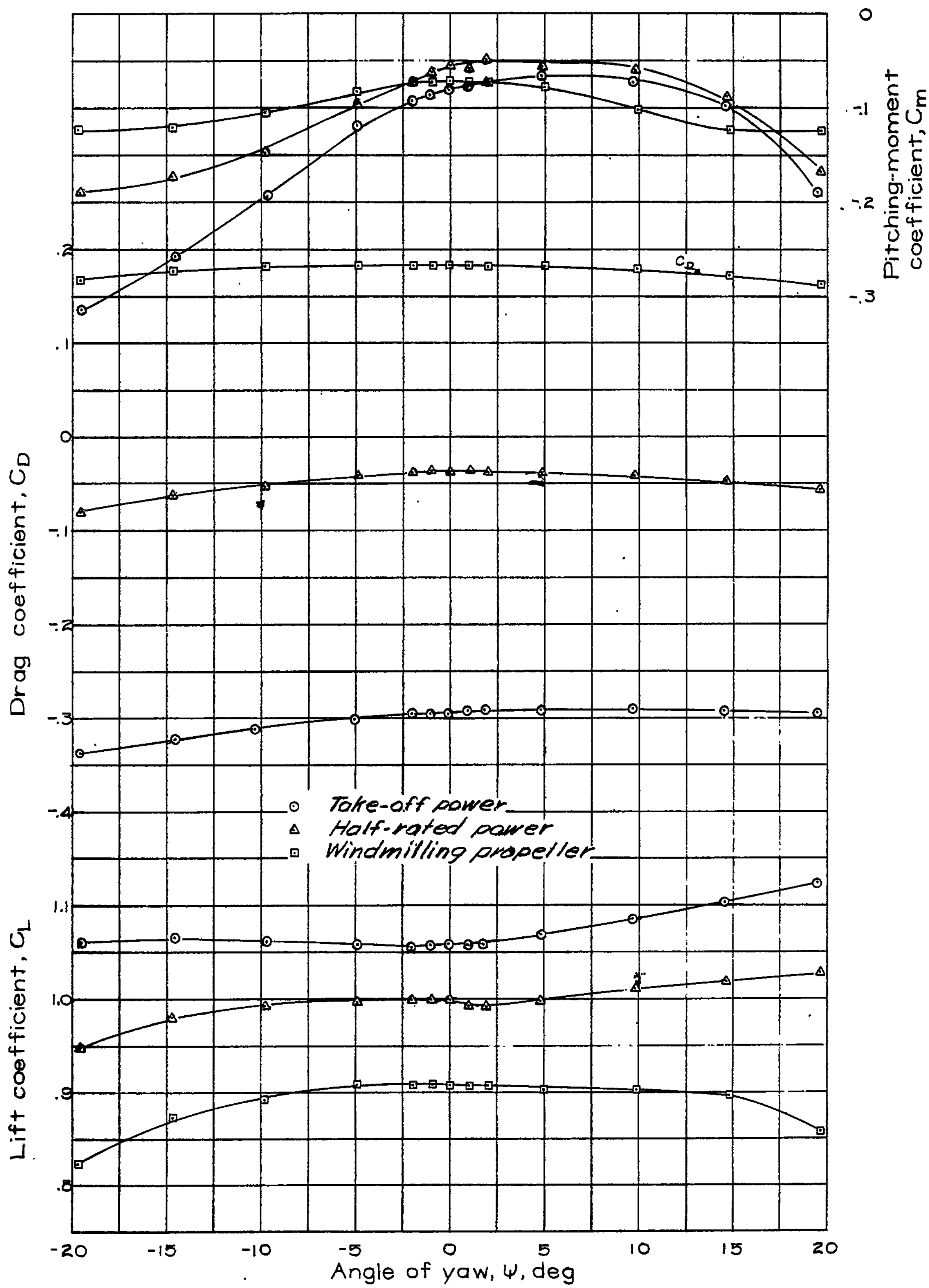

(b) Model with split flaps deflected at 45° and landing gear extended; approach condition α, 35°; β, 15°.

Figure 13.– Continued.

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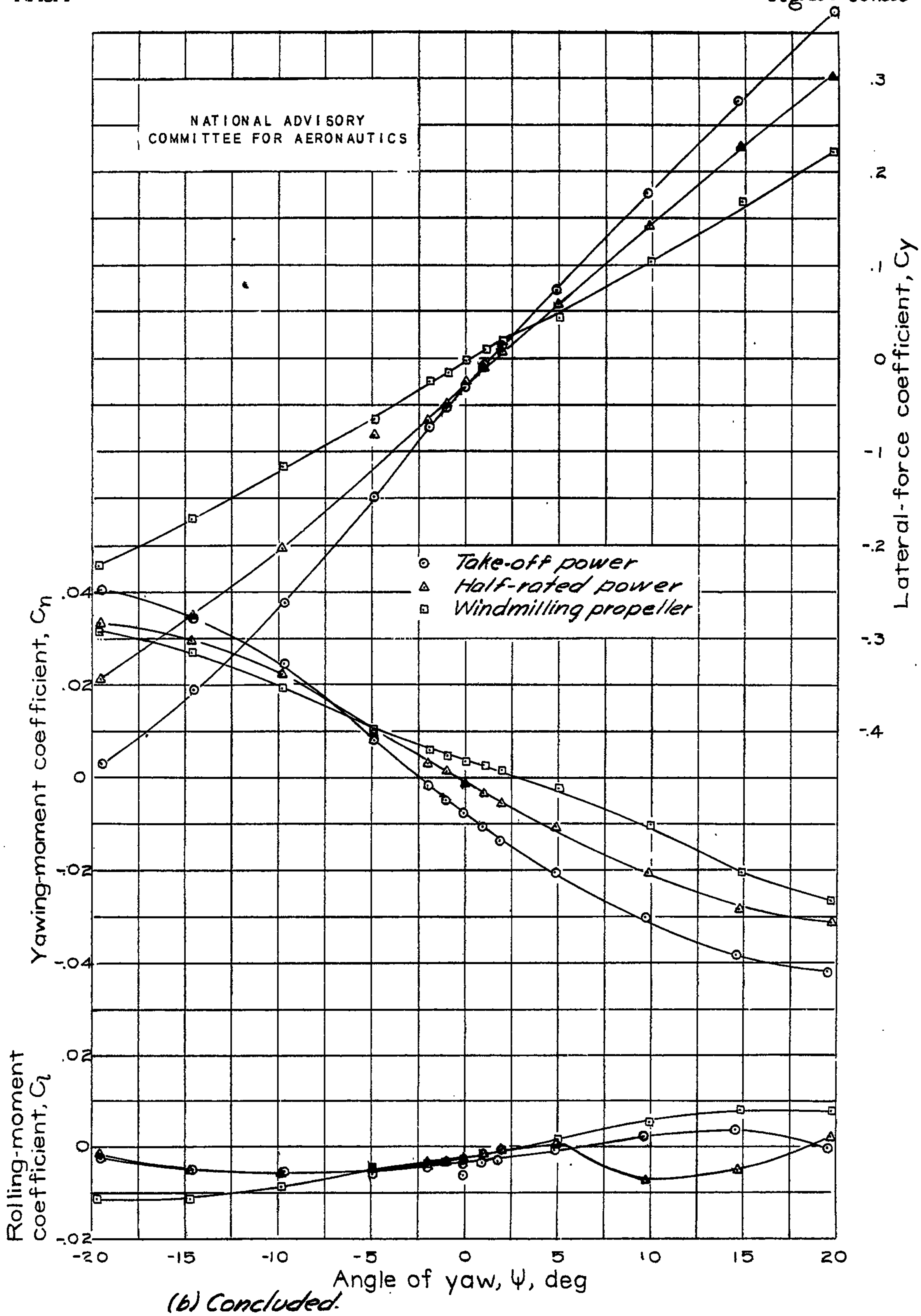

(b) Concluded.

Figure 13.- Continued.

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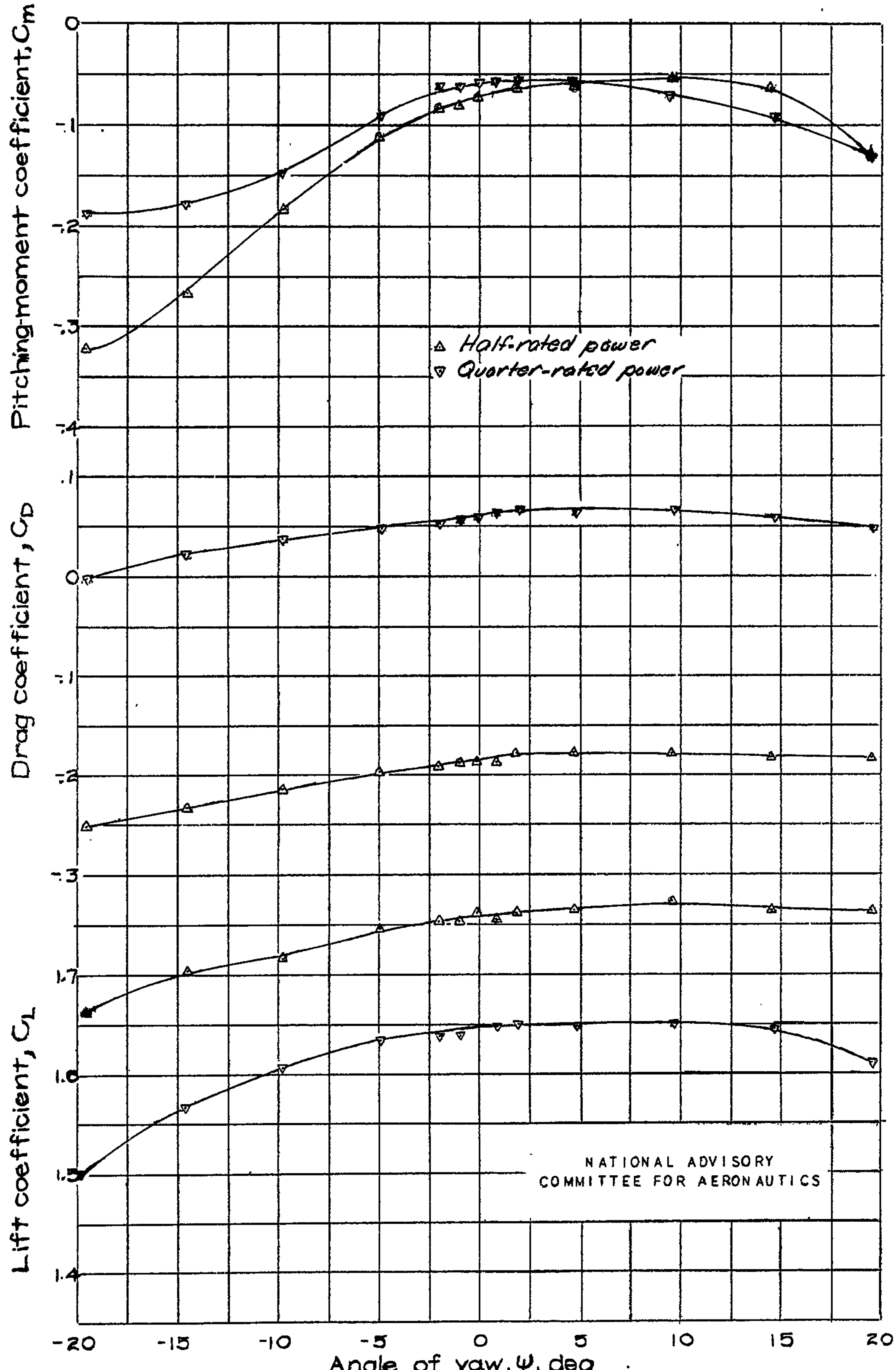

(c) Model with split flaps deflected 45° and landing gear extended. Landing attitude, α, 10.5°; β, 15°.

Figure 13.– Continued.

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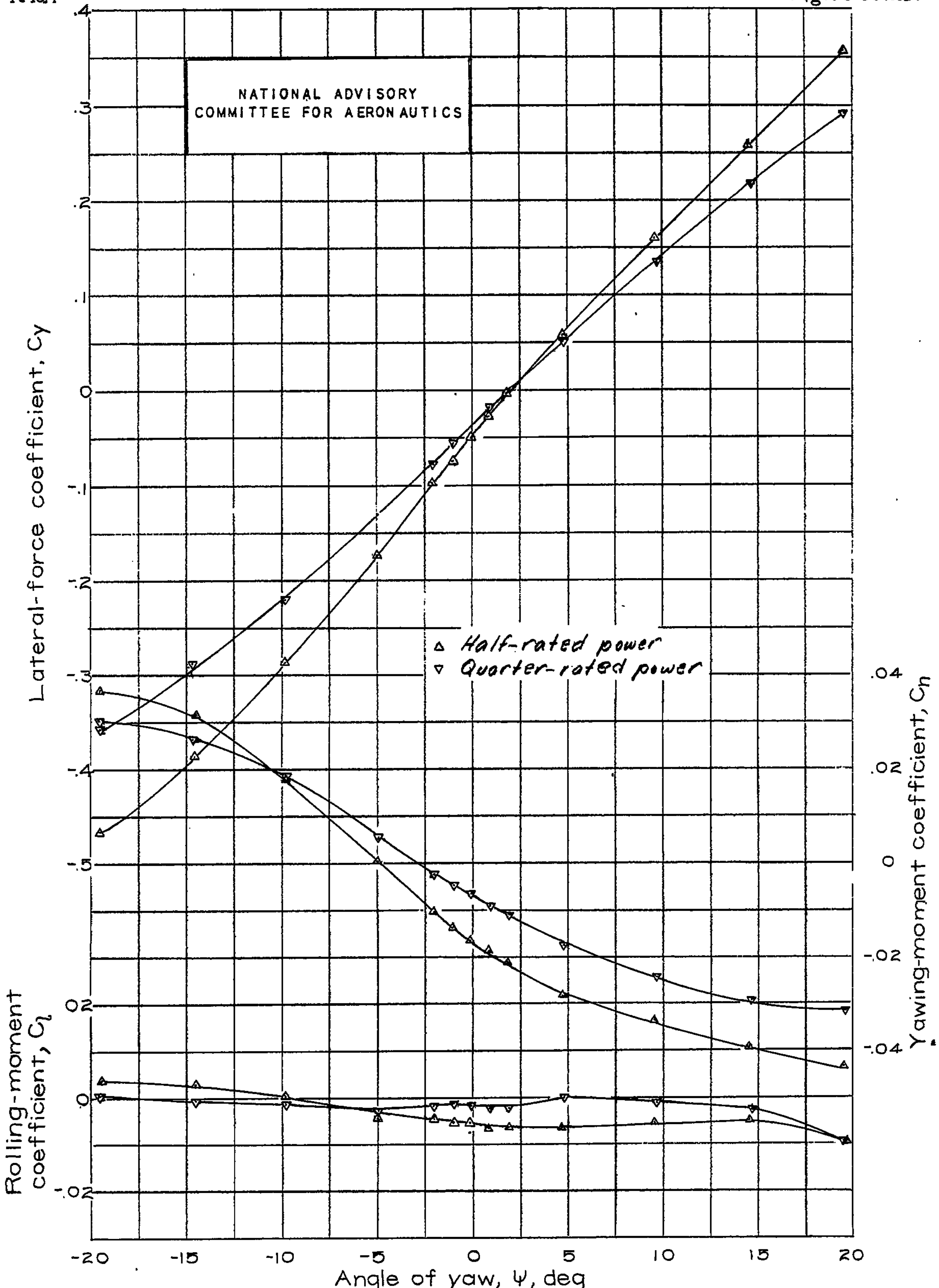

(c) Concluded.
Figure 13.– Concluded.

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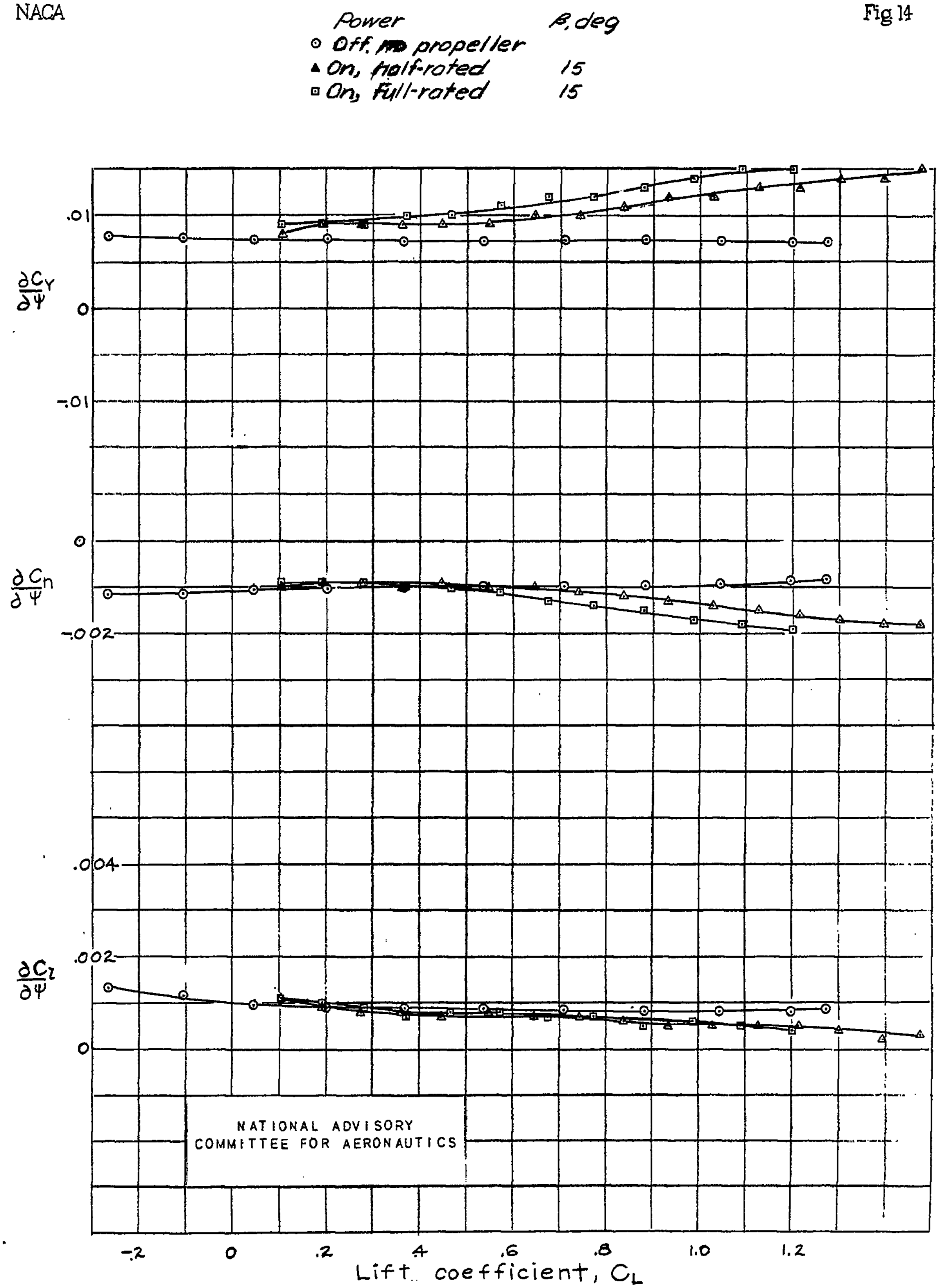

Figure 14.– Effect of propeller operation on the effective dihedral ($\partial C_l/\partial \psi$), the weathercock stability ($\partial C_n/\partial \psi$), and the slope of the lateral-force-coefficient curve ($\partial C_Y/\partial \psi$) on the clean model.

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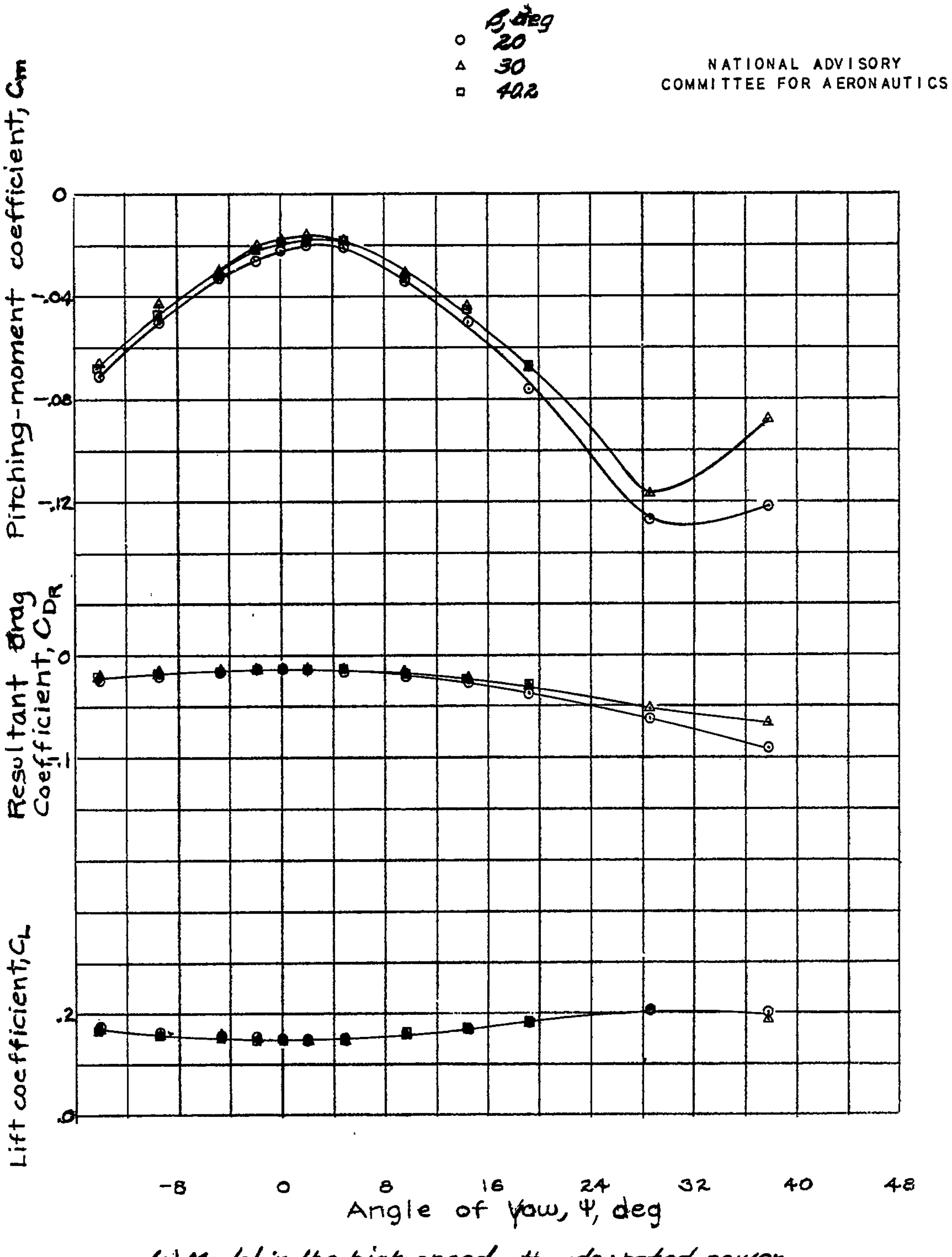
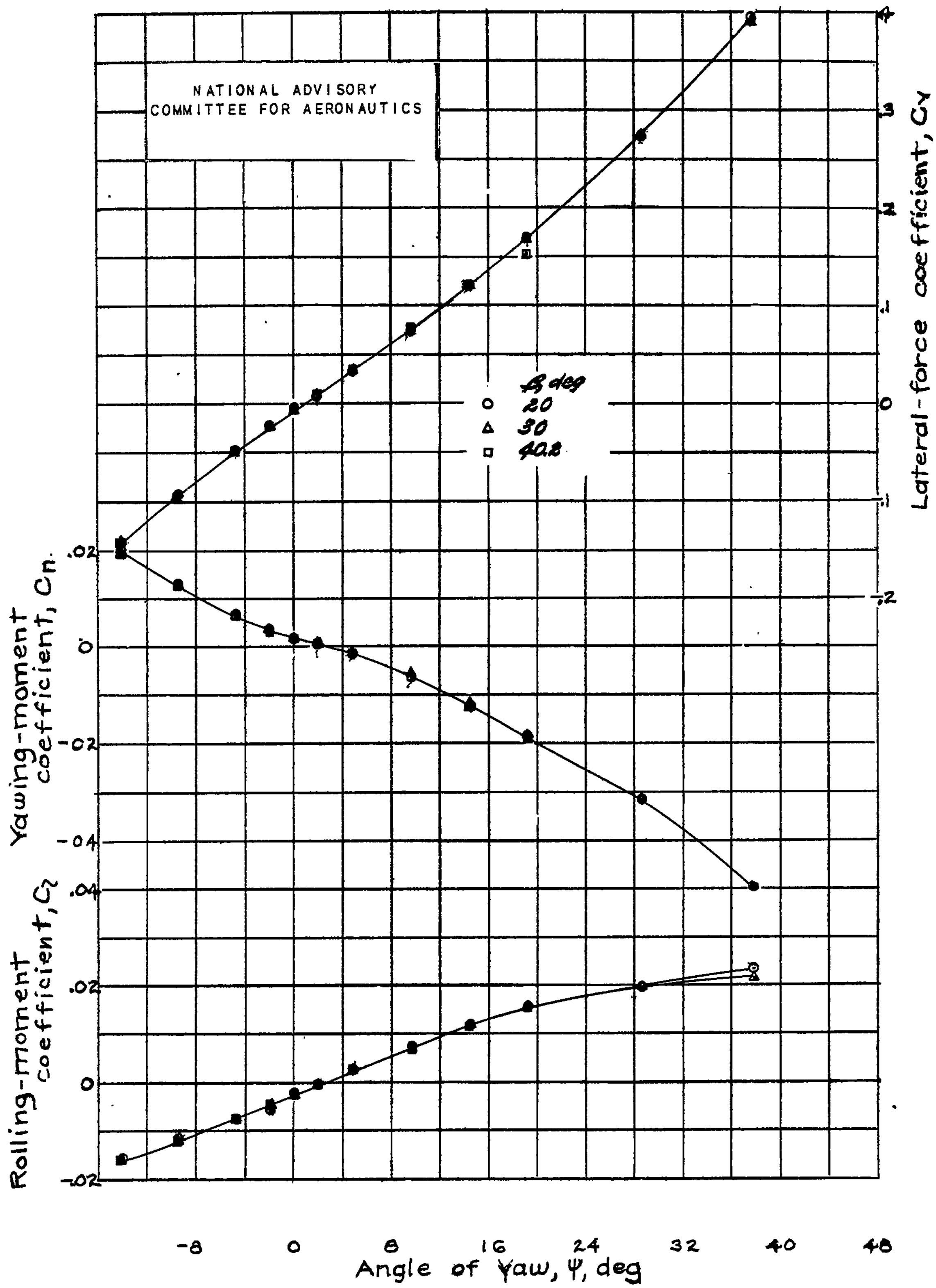


(a) Model in the high-speed attitude; rated-power.

Figure 15.– Effect of propeller blade angle on the aerodynamic characteristics of the clean model in yaw.



(a) Continued.
Figure 15. - Continued.

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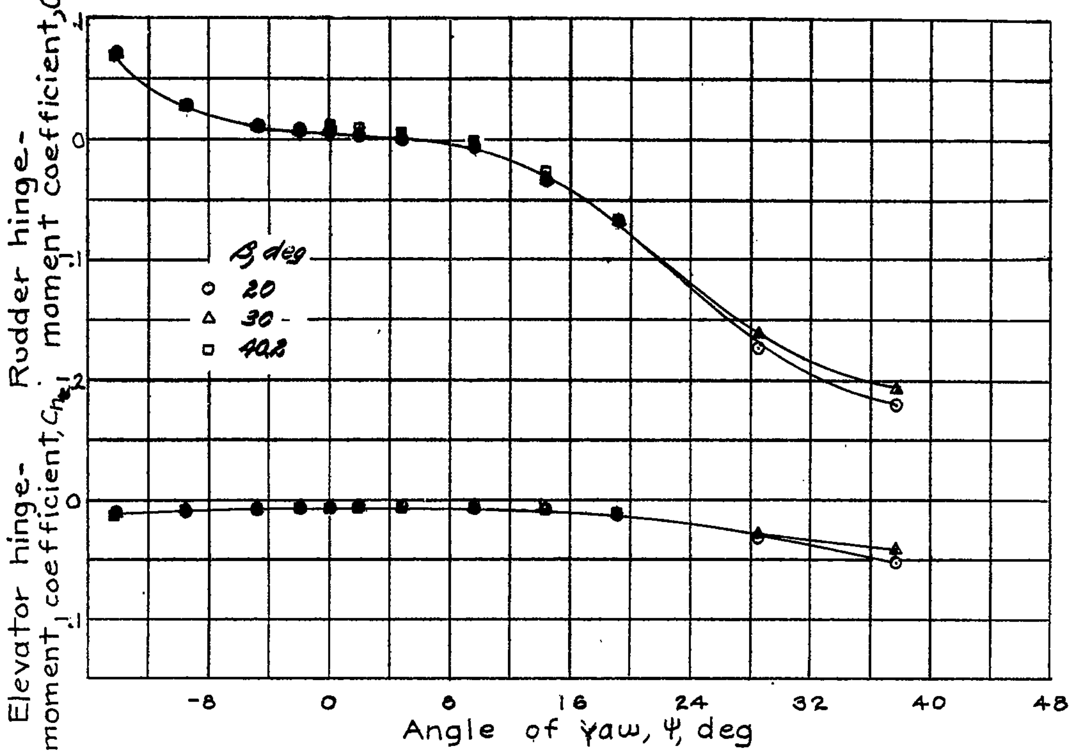
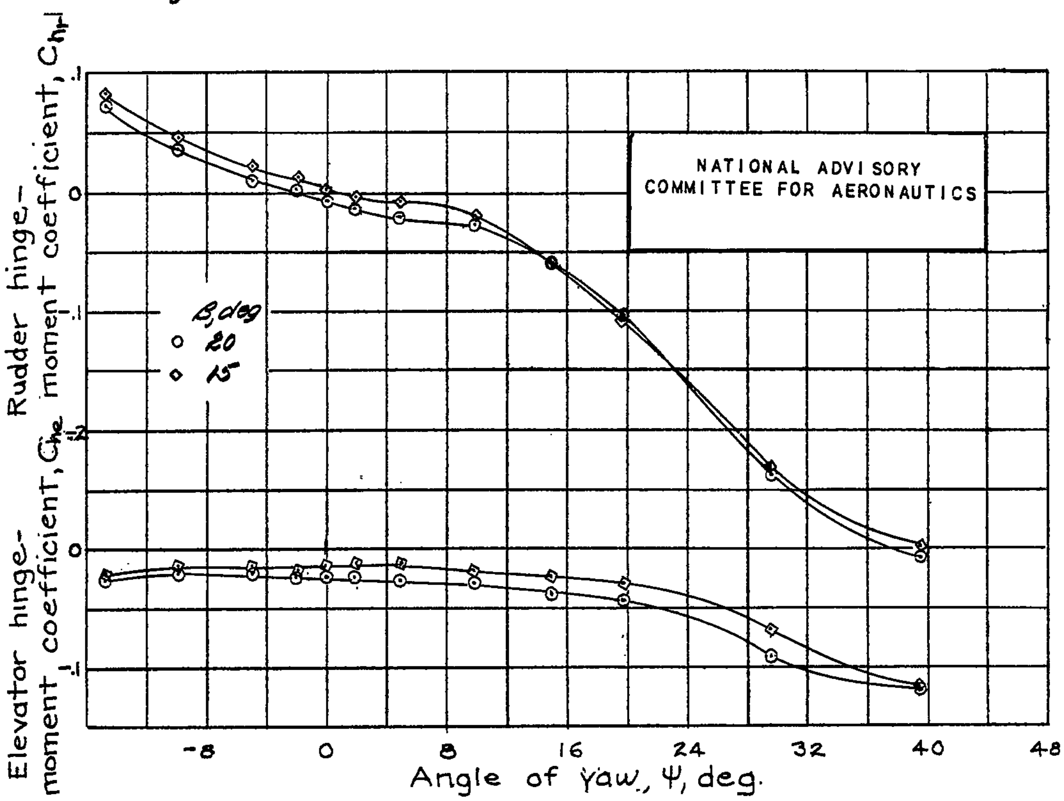


(a) Concluded.

Figure 15.- Continued.



(b) Concluded.

Figure 15.- Concluded.

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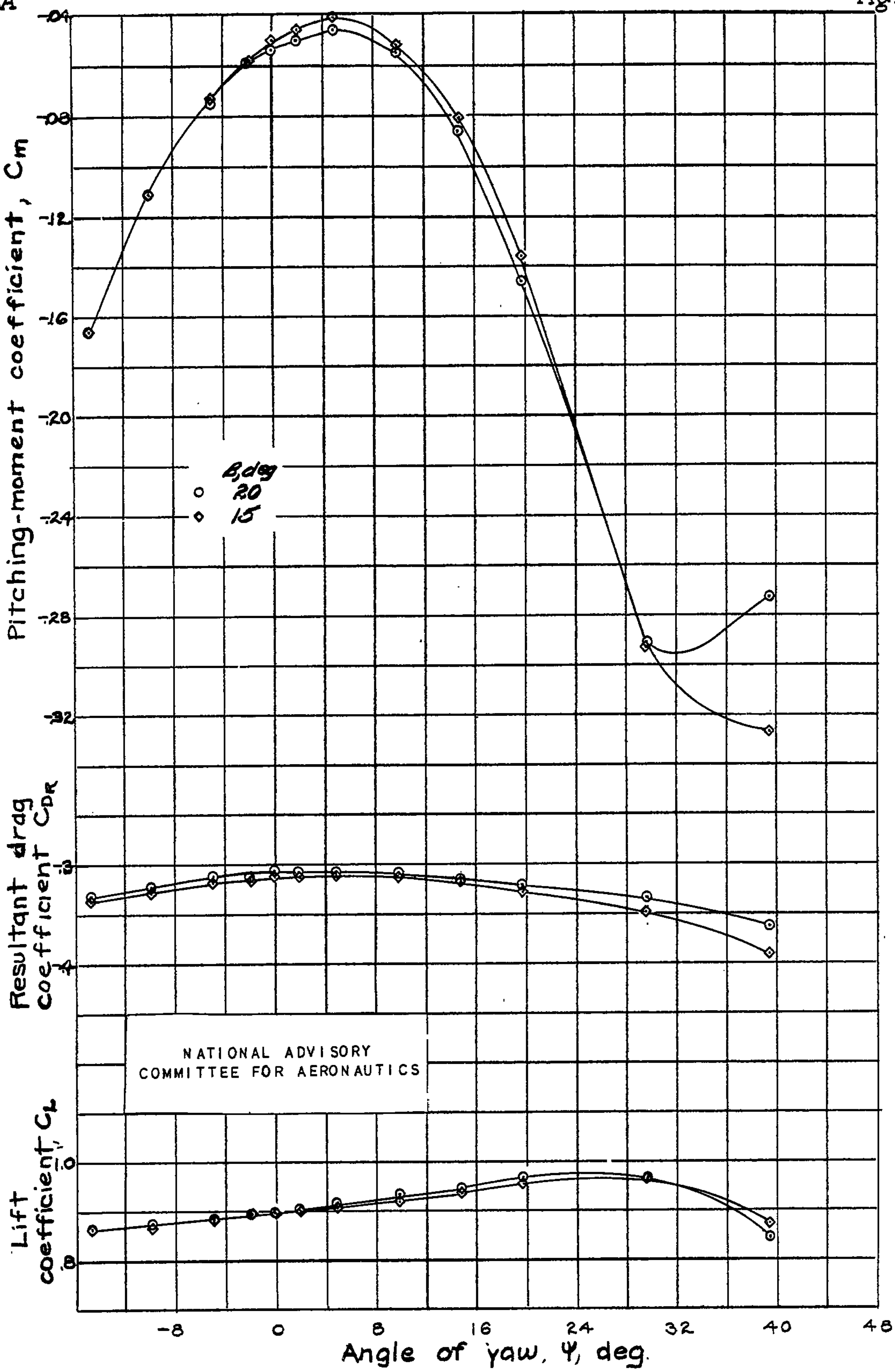
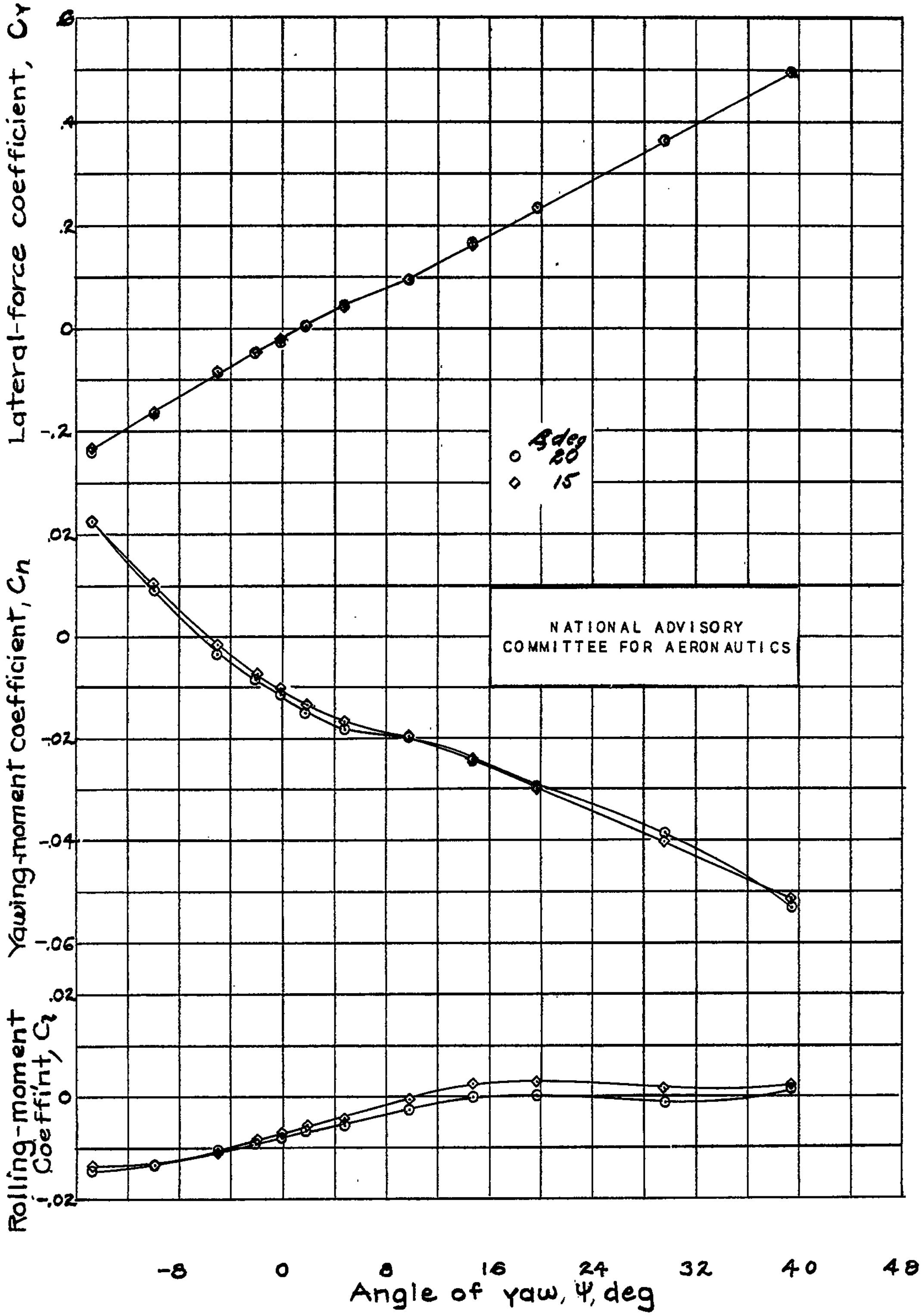


(b) Model in the climb attitude; rated power.

Figure 15.- Continued.



(b) Continued

Figure 15.- Continued.

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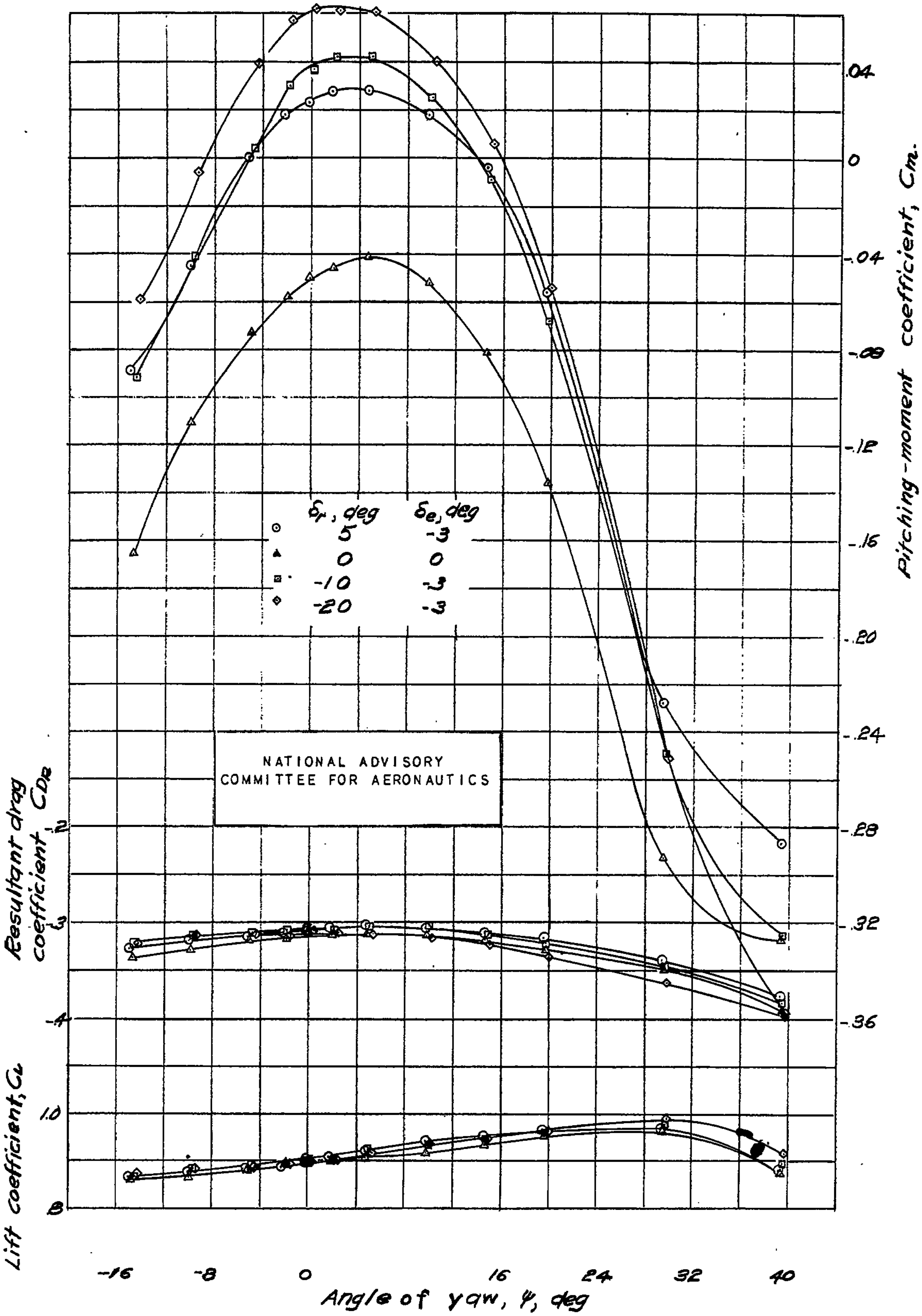


Figure 16.- Effect of rudder deflection on the aerodynamic characteristics of the clean model in yaw with rated power. Climb attitude; B 15°.

L-710

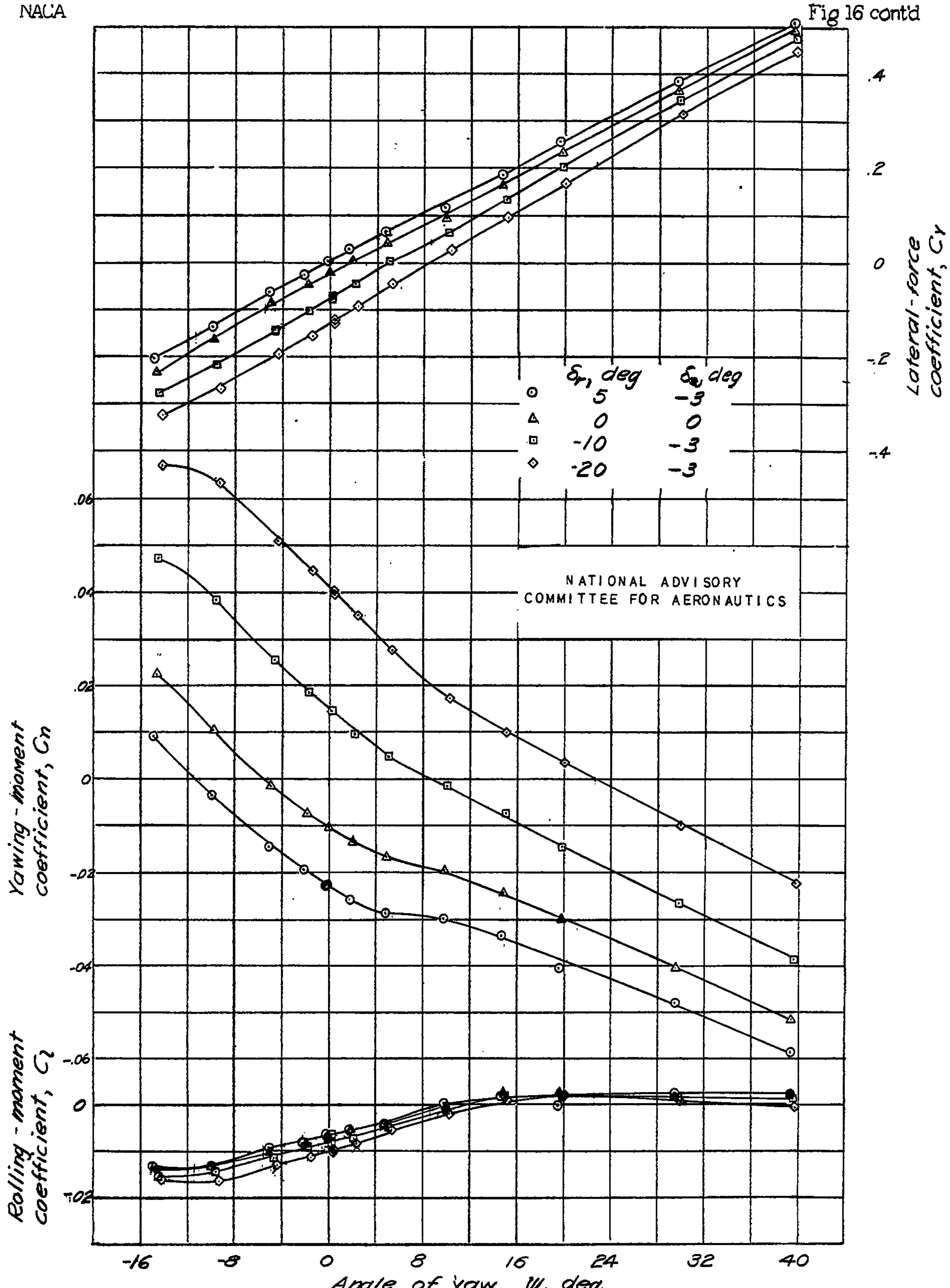


Figure 16.- Continued.

L-110

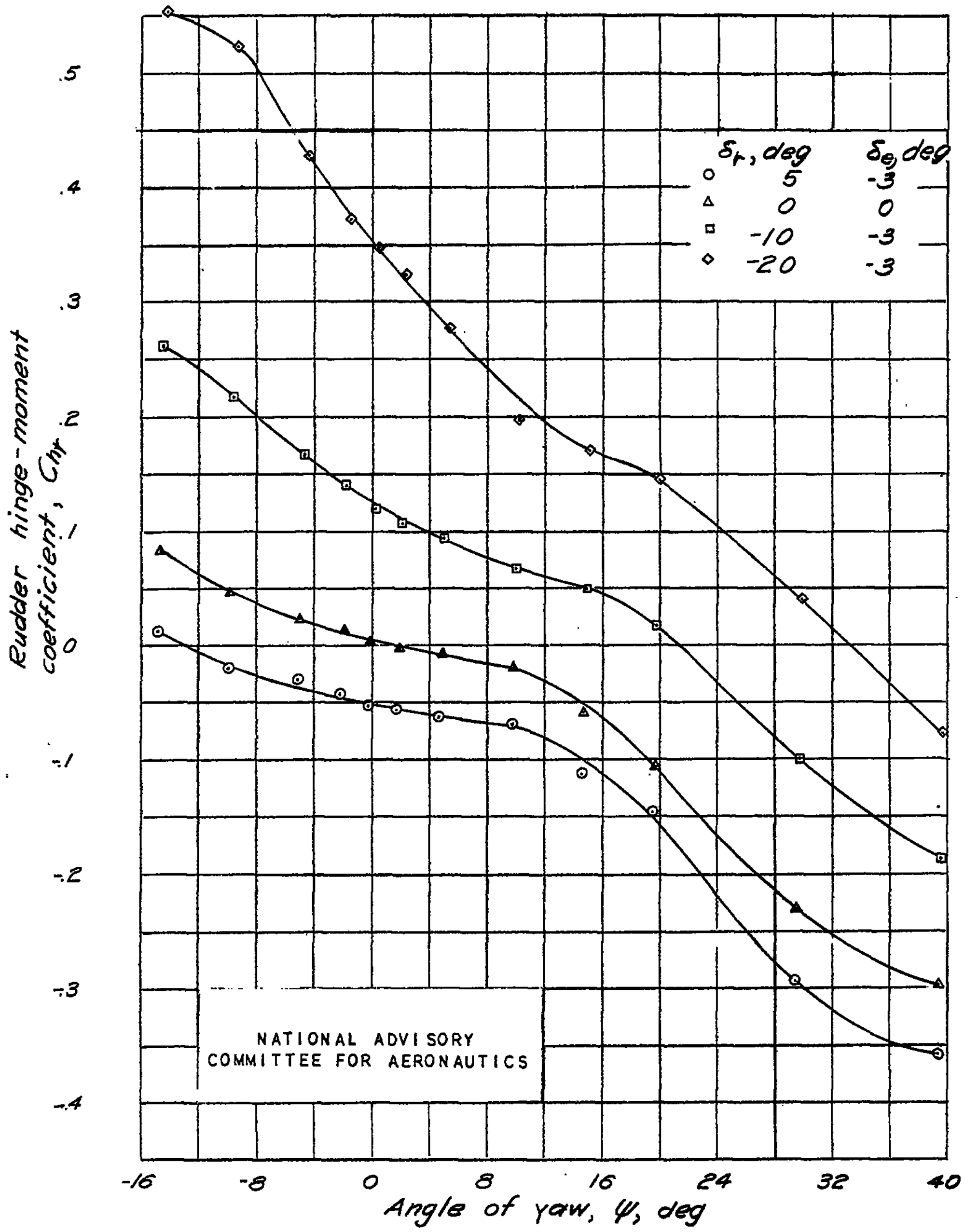
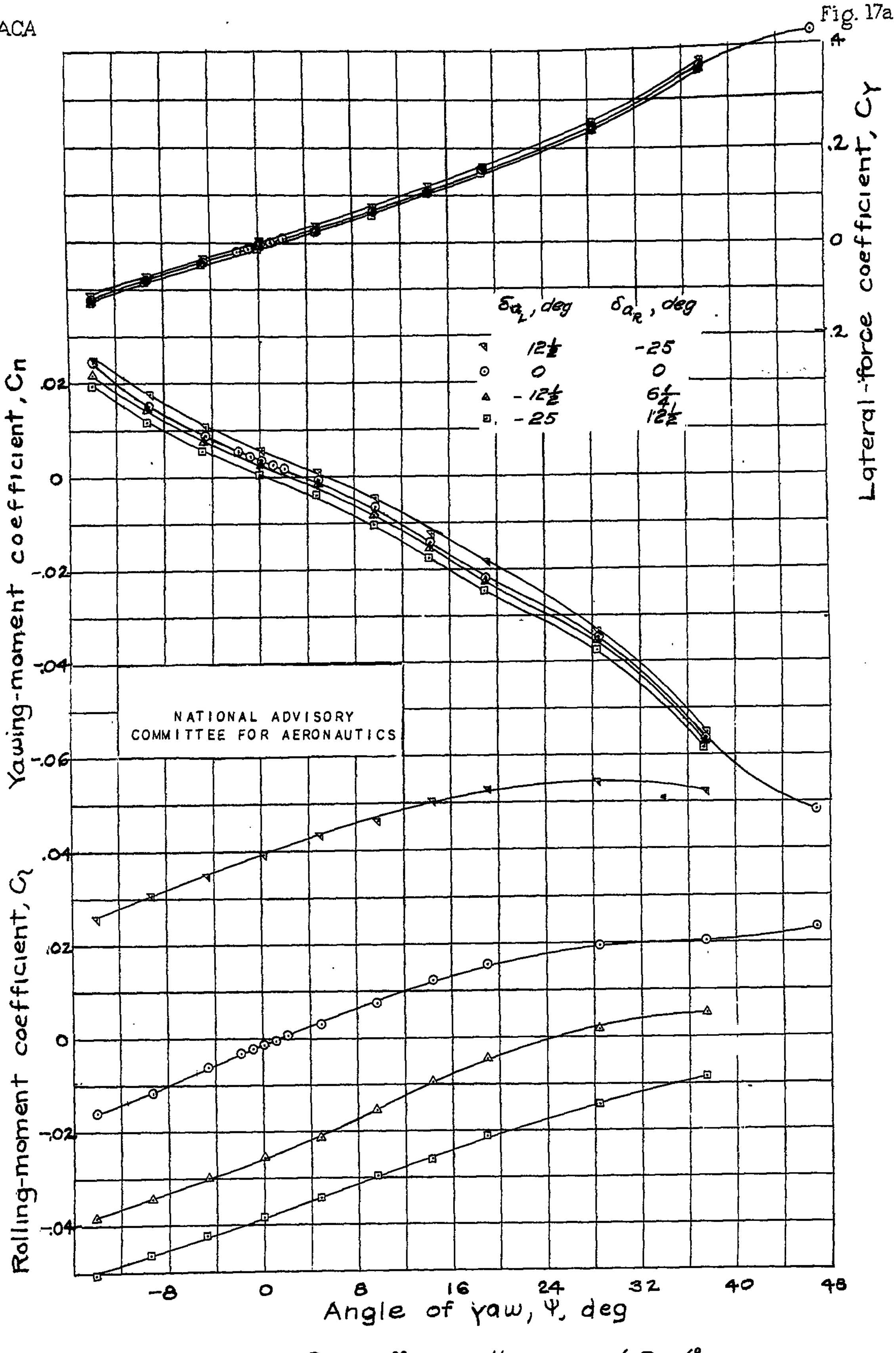


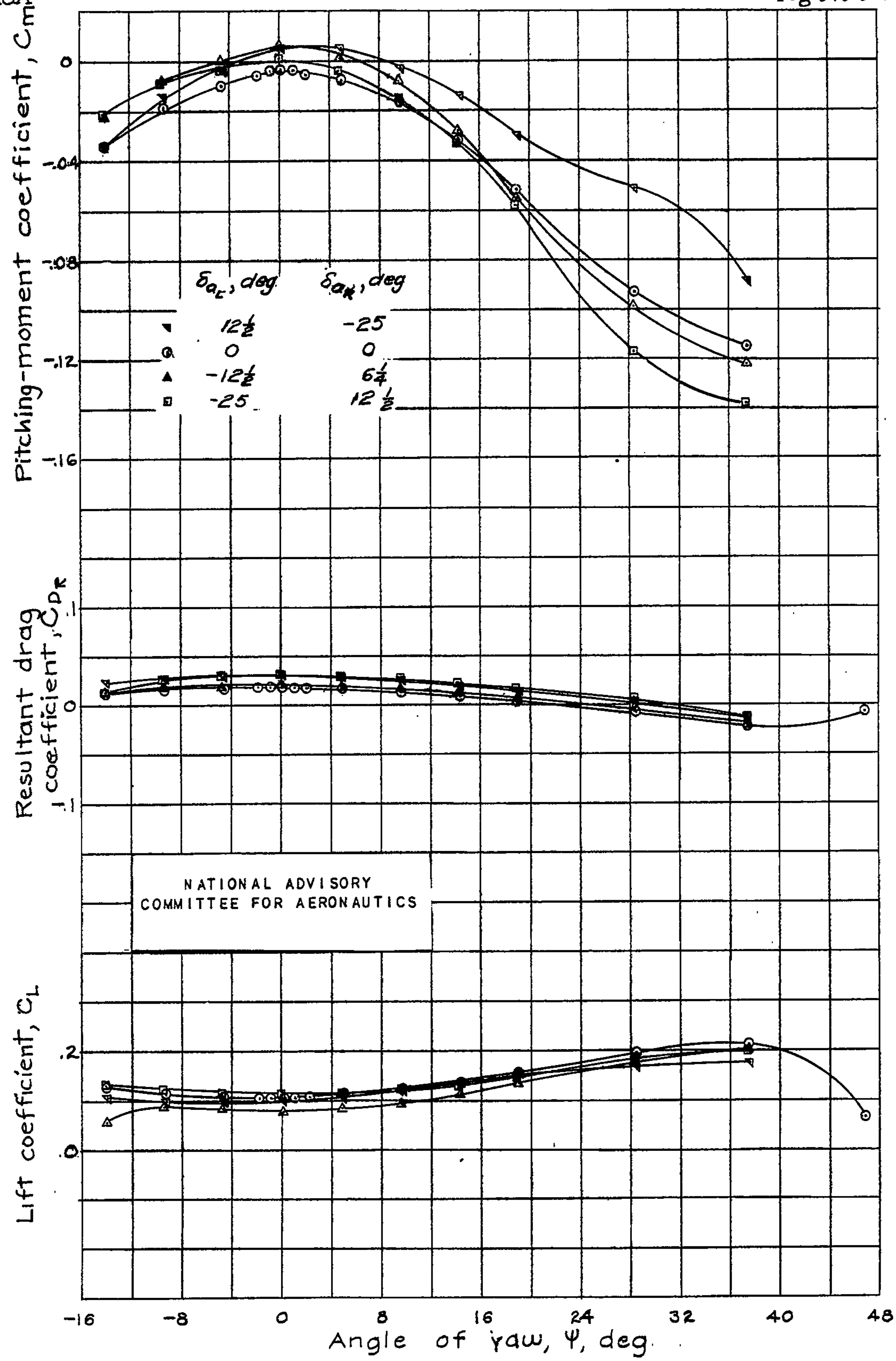
Figure 16.– Concluded.

L-710



(a) Clean model. Power off; propeller removed, δ_e, -1°

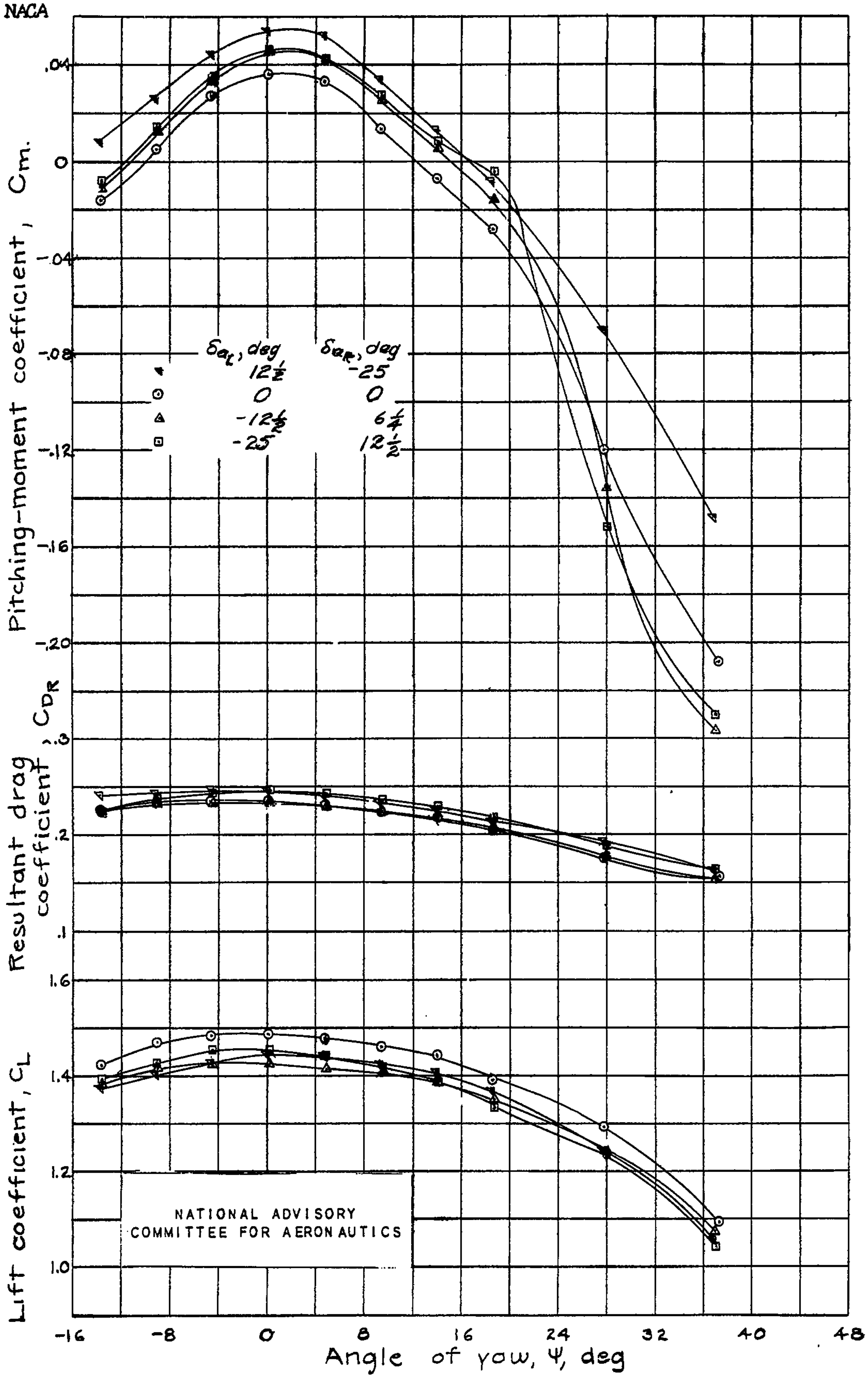
Figure 17.- Effect of aileron deflection on the aerodynamics of the model in yaw



(a) Concluded.

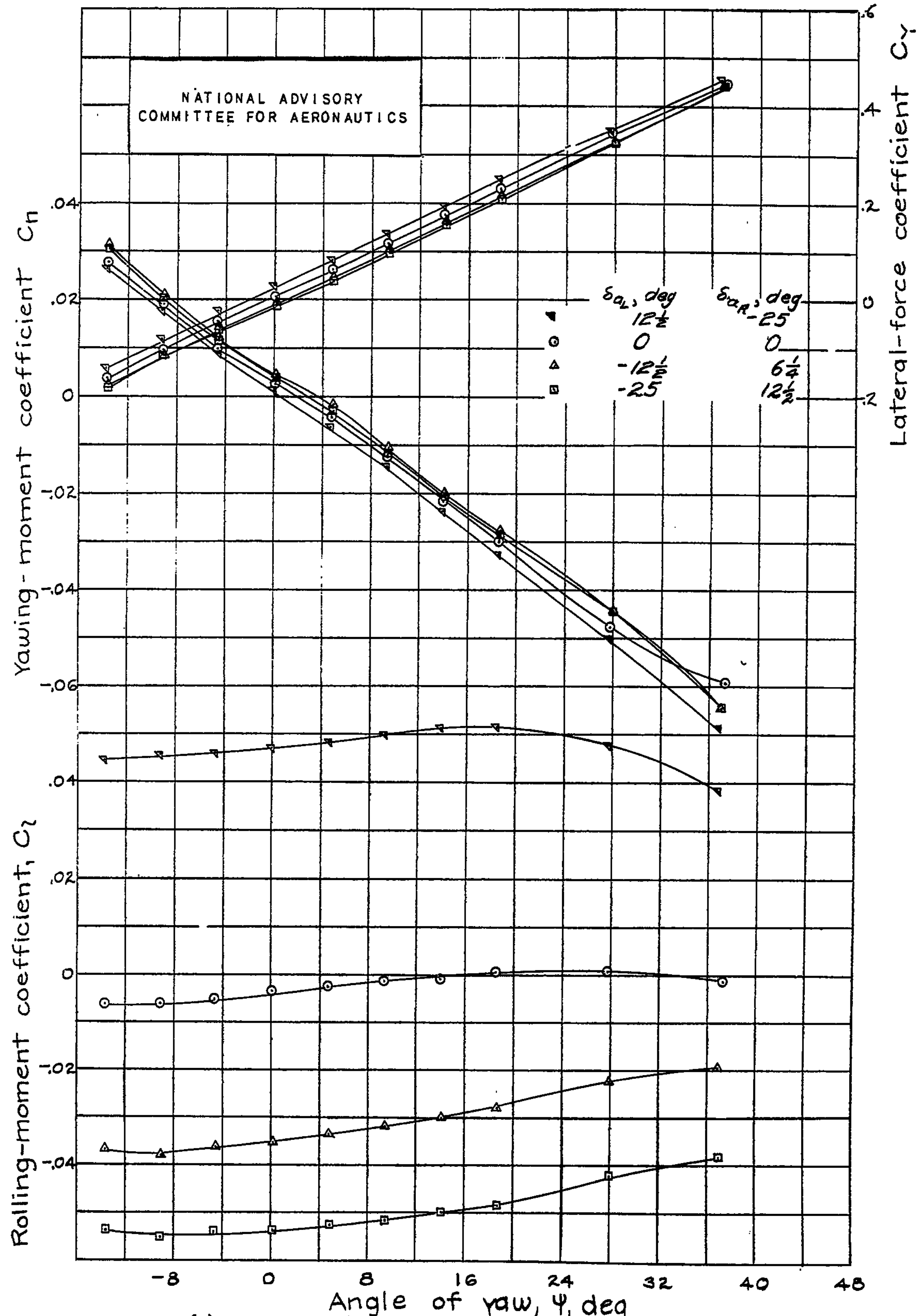
Figure 17.- Continued.

L-710



(b) Model with flaps deflected 45°. Landing gear extended; power off; propeller removed; δ_e, -10°.

Figure 17.- Continued.



(b) Concluded.

Figure 17 - Concluded.